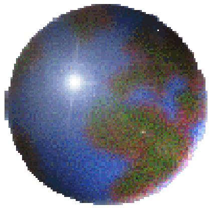


Chapter 4: Spatial Storage and Indexing

4.1 Storage: Disk and Files

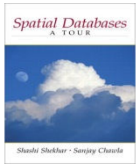
4.2 Spatial Indexing

4.3 Trends

4.4 Summary

Physical Model in 3 Level Design?

- Recall 3 levels of database design
  - Conceptual model: high level abstract description
  - Logical model: description of a concrete realization
  - Physical model: implementation using basic components
- Analogy with vehicles
  - Conceptual model: mechanisms to move, turn, stop, ...
  - Logical models:
    - Car: accelerator pedal, steering wheel, brake pedal, …
    - Bicycle: pedal forward to move, turn handle, pull brakes on handle
  - Physical models :
    - Car: engine, transmission, master cylinder, break lines, brake pads, …
    - Bicycle: chain from pedal to wheels, gears, wire from handle to brake pad
- We now go, so to speak, “under the hood”



What is a Physical Data Model?

- What is a physical data model of a database?
  - Concepts to implement logical data model
  - Using current components, e.g. computer hardware, operating systems
  - In an efficient and fault-tolerant manner
- Why learn physical data model concepts?
  - To be able to choose between DBMS brand names
    - some brand names do not have spatial indices!
  - To be able to use DBMS facilities for performance tuning
    - For example, if a query is running slow,
      - one may create an index to speed it up
    - For example, if loading of a large number of tuples takes for ever
      - one may drop indices on the table before the inserts
      - and recreate index after inserts are done!

Concepts in a Physical Data Model

- Database concepts
  - *Conceptual data model* - entity, (multi-valued) attributes, relationship, …
  - *Logical model* - relations, atomic attributes, primary and foreign keys
  - *Physical model* - secondary storage hardware, file structures, indices, …
- Examples of physical model concepts from relational DBMS
  - Secondary storage hardware: disk drives
  - File structures - sorted
  - Auxiliary search structure -
    - search trees (hierarchical collections of one-dimensional ranges)

An Interesting Fact about Physical Data Model

- Physical data model design is a trade-off between
  - Efficiently support a small set of basic operations of a few data types
  - Simplicity of overall system
- Each DBMS physical model
  - Choose a few physical DM techniques
  - Choice depends on chosen sets of operations and data types
- Relational DBMS physical model
  - Data types: numbers, strings, date, currency
    - one-dimensional, totally ordered
  - Operations:
    - search on one-dimensional totally order data types
    - insert, delete, ...

Physical Data Model for SDBMS

- Is relational DBMS physical data model suitable for spatial data?
  - Relational DBMS has simple values like numbers
  - Sorting, search trees are efficient for numbers
  - These concepts are not natural for spatial data (e.g. points in a plane)
- Reusing relational physical data model concepts
  - Space filling curves define a total order for points
  - This total order helps in using ordered files, search trees
  - But may lead to computational inefficiency!
- New spatial techniques
  - Spatial indices, e.g. grids, hierarchical collection of rectangles
  - Provide better computational performance

Common Assumptions for SDBMS Physical Model

- Spatial data
  - Dimensionality of space is low, e.g. 2 or 3
  - Data types: OGIS data types
  - Approximations for extended objects (e.g. linestrings, polygons)
    - Minimum Orthogonal Bounding Rectangle (MOBR or MBR)
    - MBR(O) is the smallest axis-parallel rectangle enclosing an object O
  - Supports filter and refine processing of queries
- Spatial operations
  - OGIS operations, e.g. topological, spatial analysis
  - Many topological operations are approximated by “Overlap”
  - Common spatial queries - listed in next slide

Common Spatial Queries and Operations

- Physical model provides simpler operations needed by spatial queries!
- Common Queries
  - *Point query:* Find all rectangles containing a given point
  - *Range query:* Find all objects within a query rectangle
  - *Nearest neighbor:* Find the point closest to a query point
  - *Intersection query:* Find all the rectangles intersecting a query rectangle
- Common operations across spatial queries
  - *find* : retrieve records satisfying a condition on attribute(s)
  - *findnext* : retrieve next record in a dataset **with total order**
    - after the last one retrieved via previous find or findnext
  - *nearest neighbor* of a given object in a **spatial** dataset

Scope of Discussion

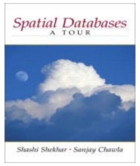
- Learn basic concepts in physical data model of SDBMS
- Review related concepts from physical DM of relational DBMS
- Reusing relational physical data model concepts
  - Space filling curves define a total order for points
  - This total order helps in using ordered files, search trees
  - But may lead to computational inefficiency!
- New techniques
  - Spatial indices, e.g. grids, hierarchical collection of rectangles
  - Provide better computational performance

Storage Hierarchy in Computers

- Computers have several components
  - Central Processing Unit (CPU)
  - Input, output devices, e.g. mouse, keyword, monitors, printers
  - Communication mechanisms, e.g. internal bus, network card, modem
  - Storage Hierarchy
- Types of storage Devices
  - *Main memories* - fast but content is lost when power is off
  - *Secondary storage* - slower, retains content without power
  - *Tertiary storage* - very slow, retains content, very large capacity
- DBMS usually manage data
  - On secondary storage, e.g. disks
  - Use main memory to improve performance
  - User tertiary storage (e.g. tapes) for backup, archival etc.

Secondary Storage Hardware: Disk Drives

- Disk concepts
  - Circular platters with magnetic storage medium
  - Multiple platters are mounted on a spindle
  - Platters are divided into concentric tracks
  - A cylinder is a collection of tracks across platters with common radium
  - Tracks are divided into sectors
  - A sector size may a few kilobytes
- Disk drive concepts
  - Disk heads to read and write
  - There is disk head for each platter (recording surface)
  - A head assembly moves all the heads together in radial direction
  - Spindle rotates at a high speed, e.g. thousands revolution per minute
- Accessing a sector has three major steps:
  - Seek: Move head assembly to relevant track
  - Latency: Wait for spindle to rotate relevant sector under disk head
  - Transfer: Read or write the sector
  - Other steps involve communication between disk controller and CPU



Using Disk Hardware Efficiently

- Disk access cost are affected by
  - Placement of data on the disk
  - Fact than seek cost > latency cost > transfer (See Table 4.2, pp.86)
  - A few common observations follow
- Size of sectors
  - Larger sector provide faster transfer of large data sets
  - But waste storage space inside sectors for small data sets
- Placement of most frequently accessed data items
  - On middle tracks rather than innermost or outermost tracks
  - Reason: minimize average seek time
- Placement of items in a large data set requiring many sectors
  - Choose sectors from a single cylinder
  - Reason: Minimize seek cost in scanning the entire data set.

Software View of Disks: Fields, Records and File

- Views of secondary storage (e.g. disks)
  - Hardware views - discussed in last few slides
  - Software views - Data on disks is organized into fields, records, files
- Concepts
  - Field presents a property or attribute of a relation or an entity
  - Records represent a row in a relational table
    - collection of fields for attributes in relational schema of the table
  - Files are collections of records
    - homogeneous collection of records may represent a relation
    - heterogeneous collections may be a union of related relations

Mapping Records and Files to Disk

- Records
  - Often smaller than a sector
  - Many records in a sector
- Files with many records
  - Many sectors per file
- File system
  - Collection of files
  - Organized into directories
- Mapping tables to disk
  - Figure 4.1
  - City table takes 2 sectors
  - Others take 1 sector each

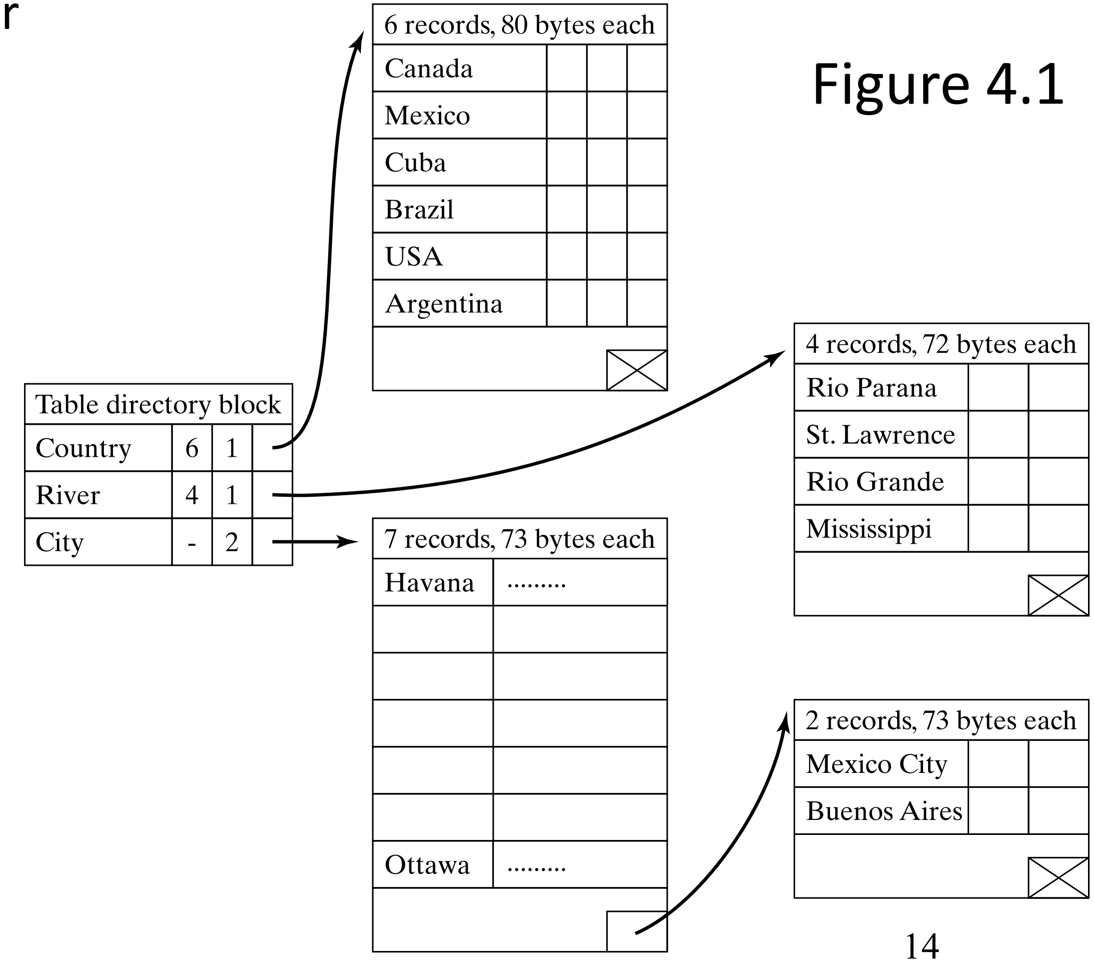


Figure 4.1

Buffer Management

- Motivation
  - Accessing a sector on disk is much slower than accessing main memory
  - Idea: keep repeatedly accessed data in main memory buffers
    - to improve the completion time of queries
    - reducing load on disk drive
- Buffer Manager software module decides
  - Which sectors stay in main memory buffers?
  - Which sector is moved out if we run out of memory buffer space?
  - When to pre-fetch sector before access request from users?
  - These decision are based on the disk access patterns of queries!

File Structures

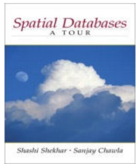
- What is a file structure?
  - A method of organizing records in a file
  - For efficient implementation of common file operations on disks
  - Example: ordered files
- Measure of efficiency
  - I/O cost: Number of disk sectors retrieved from secondary storage
  - CPU cost: Number of CPU instruction used
  - See Table 4.1 for relative importance of cost components
  - Total cost = sum of I/O cost and CPU cost

File Structures – Selected File Operations

- Common file operations
  - Find: key value --> record matching key values
  - Findnext --> Return next record after find if records were sorted
  - Insert --> Add a new record to file without changing file-structure
  - Nearest neighbor of a object in a spatial dataset
- Examples using Figure 4.1, pp.88
  - find(Name=Canada) on Country table returns record about Canada
  - findnext() on Country table returns record about Cuba
    - since Cuba is next value after Canada in sorted order of Name
  - insert(record about Panama) into Country table
    - adds a new record
    - location of record in Country file depends on file-structure
  - Nearest neighbor Argentina in country table is Brazil

Common File Structures

- Common file structures
  - Heap or unordered or unstructured
  - Ordered
  - Hashed
  - Clustered
  - Descriptions follow
- Basic comparison of common File Structures
  - Heap file is efficient for inserts and used for logfiles
    - but find, findnext, etc. are very slow
  - Hashed files are efficient for find, insert, delete etc.
    - but findnext is very slow
  - Ordered file organization are very fast for findnext
    - and pretty competent for find, insert, etc.



File Structures: Heap, Ordered

- Heap
  - Records are in no particular order (example: Figure 4.1)
  - Insert can simple add record to the last sector
  - find, findnext, nearest neighbor scan the entire files
- Ordered
  - Records are sorted by a selected field (example: Figure 4.3 below)
  - findnext can simply pick up physically next record
  - find, insert, delete may use binary search, is very efficient
  - nearest neighbor processed as a range query (see pp.95 for details)

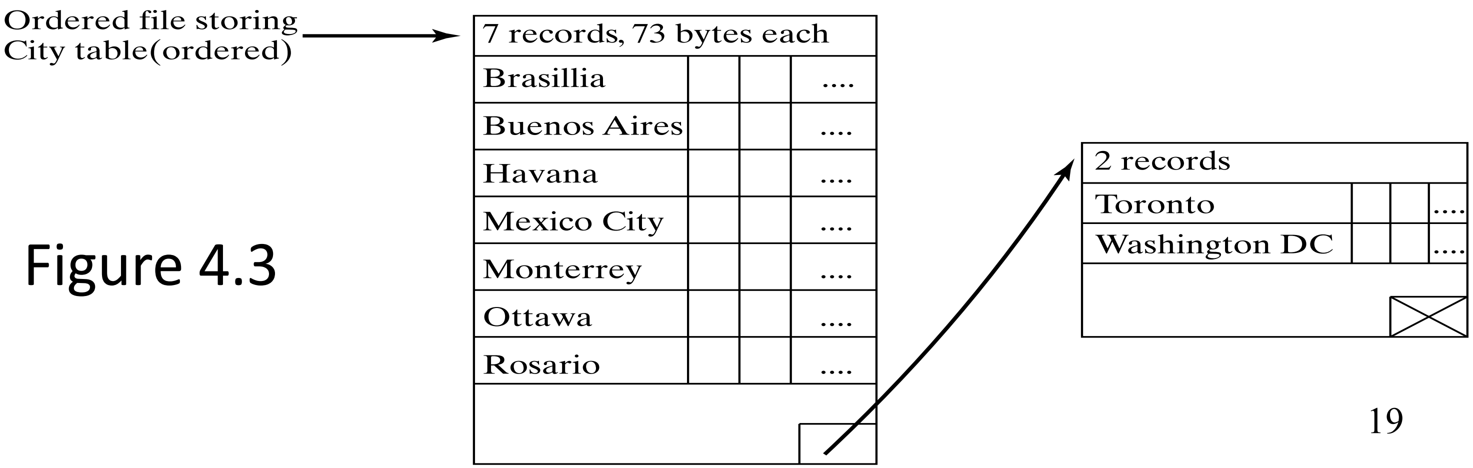


Figure 4.3

File Structure : Hash

- Components of a Hash file structure (Figure 4.2)
  - A set of buckets (sectors)
  - Hash function : key value --> bucket
  - Hash directory: bucket --> sector
- Operations
  - find, insert, delete are fast
    - compute hash function
    - lookup directory
    - fetch relevant sector
  - findnext, nearest neighbor are slow
    - no order among records

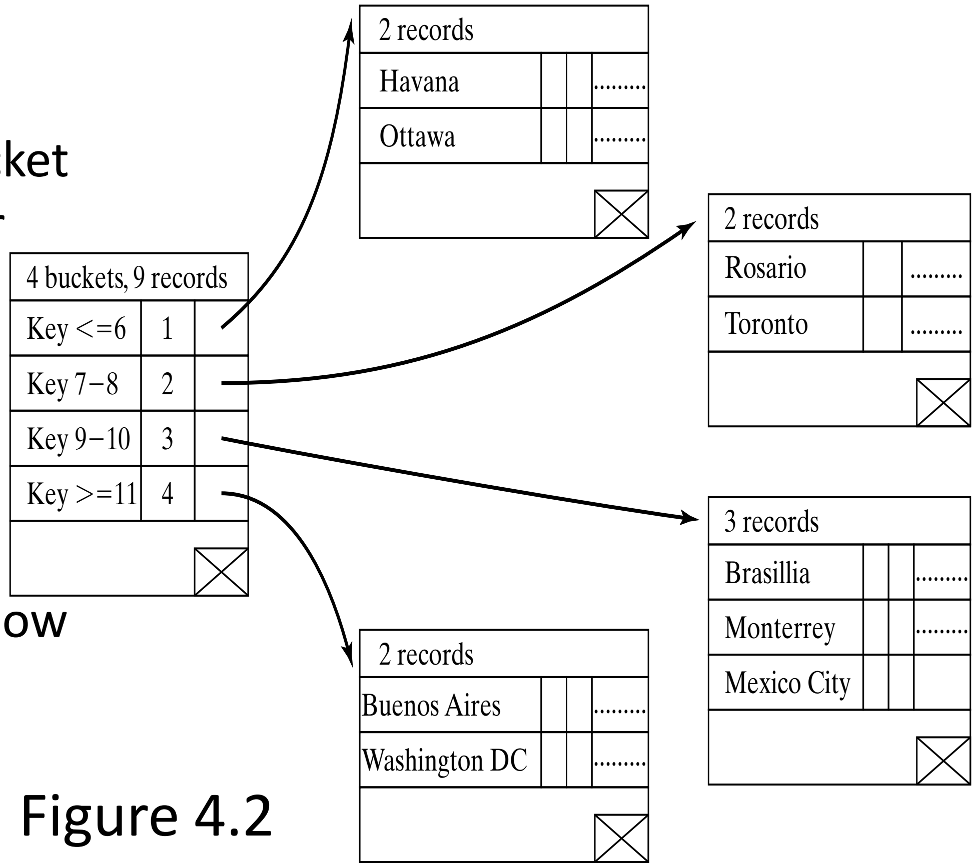


Figure 4.2

Spatial File Structures: Clustering

- Motivation:
  - Ordered files are not natural for spatial data
  - Clustering records in sector by space filling curve is an alternative
  - In general, clustering groups records
    - accessed by common queries
    - into common disk sectors
    - to reduce I/O costs for selected queries
- Clustering using Space filling curves
  - Z-curve
  - Hilbert-curve
  - Details on following 3 slides

Z-Curve

- What is a Z-curve?
  - A space filling curve
  - Generated from interleaving bits
    - x, y coordinate
    - see Figure 4.6
  - Alternative generation method
    - see Figure 4.5
  - Connecting points by z-order
    - see Figure 4.4
    - looks like Ns or Zs
- Implementing file operations
  - similar to ordered files

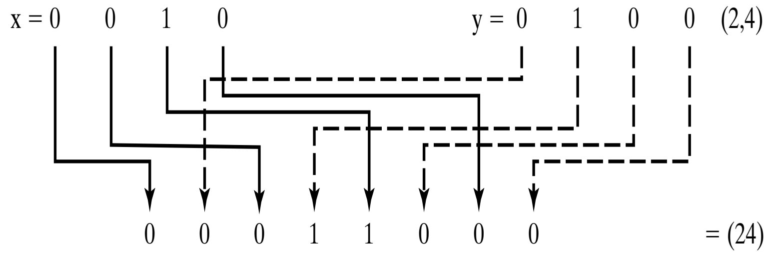
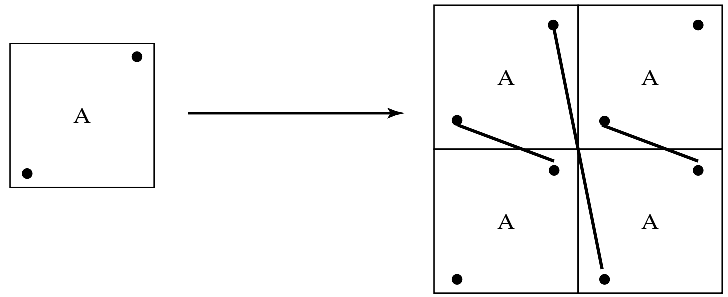


Figure 4.6



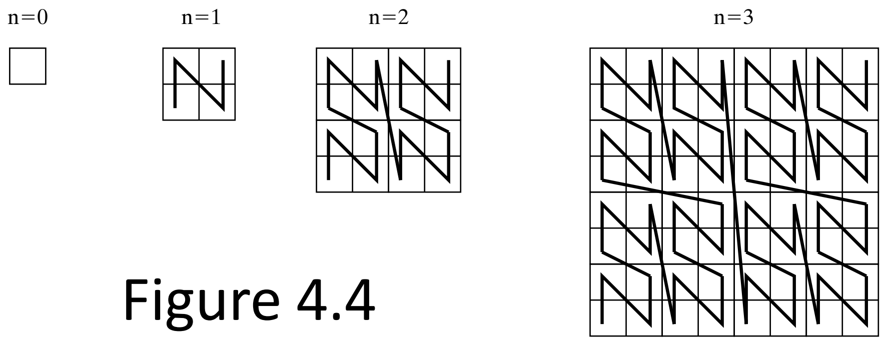
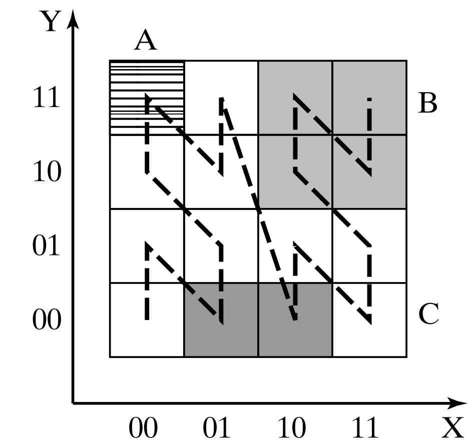


Figure 4.4

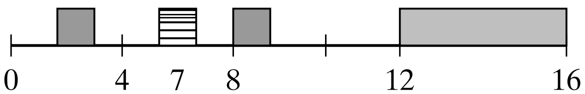
Example of Z-values

- Figure 4.7
  - Left part shows a map with spatial object A, B, C
  - Right part and left bottom part Z-values within A, B and C
  - Note C gets z-values of 2 and 8, which are not close
  - Exercise: Compute z-values for B.

Figure 4.7



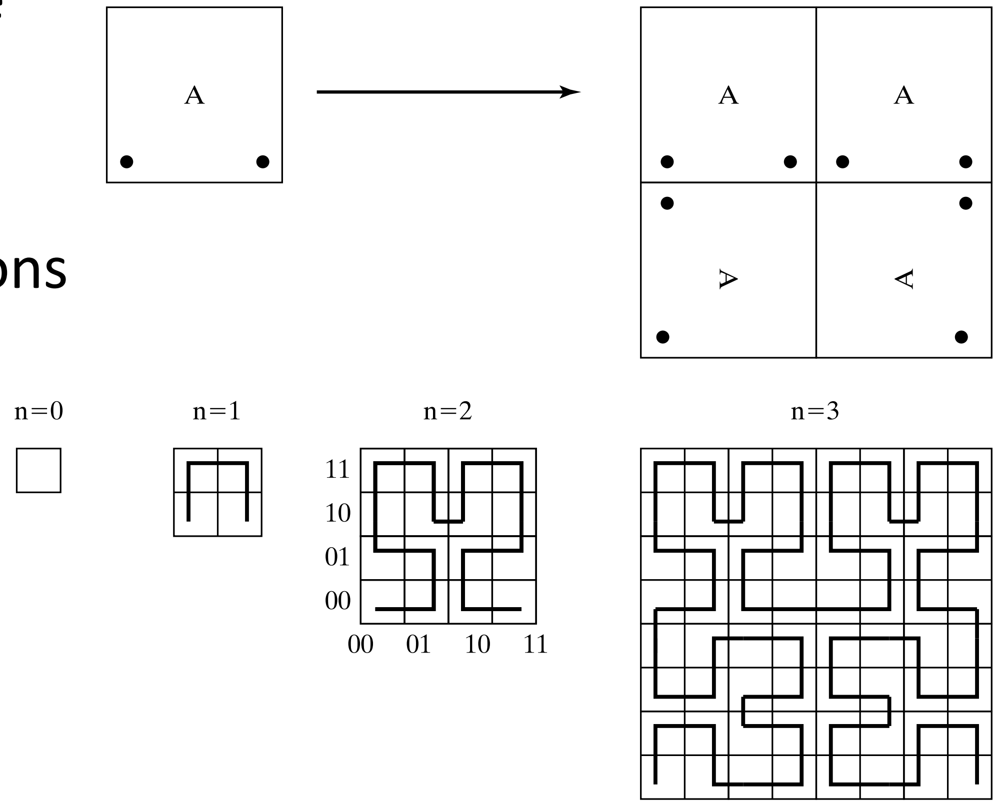
Object	Points	x	y	interleave	z-value
A	1	00	11	0101	5
B	1				
	2				
	3				
	4				
C	1	01	00	0010	2
	2	10	00	1000	8



Hilbert Curve

- A space filling curve
  - Example: Figure 4.5
- More complex to generate
  - Due to rotations
  - See details on pp.92-93
  - Illustration on next slide!
- Implementing file operations
  - Similar to ordered files

Figure 4.5



Calculating Hilbert Values

Procedure on pp.92

Figure 4.8

y \ x	00	01	10	11
00	0000	0010	1001	1010
01	0001	0011	1001	1011
10	0100	0110	1100	1110
11	0101	0111	1101	1111

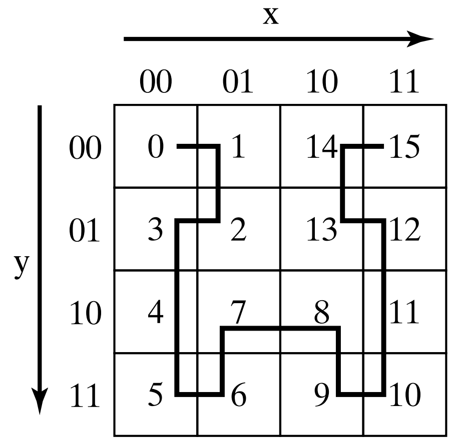
(a)

y \ x	00	01	10	11
00	00	03	30	33
01	01	02	31	32
10	10	13	20	23
11	11	12	21	22

(b)

y \ x	00	01	10	11
00	00	01	32	33
01	03	02	31	30
10	10	13	20	23
11	11	12	21	22

(c)



(d)

Handling Regions with Z-curve

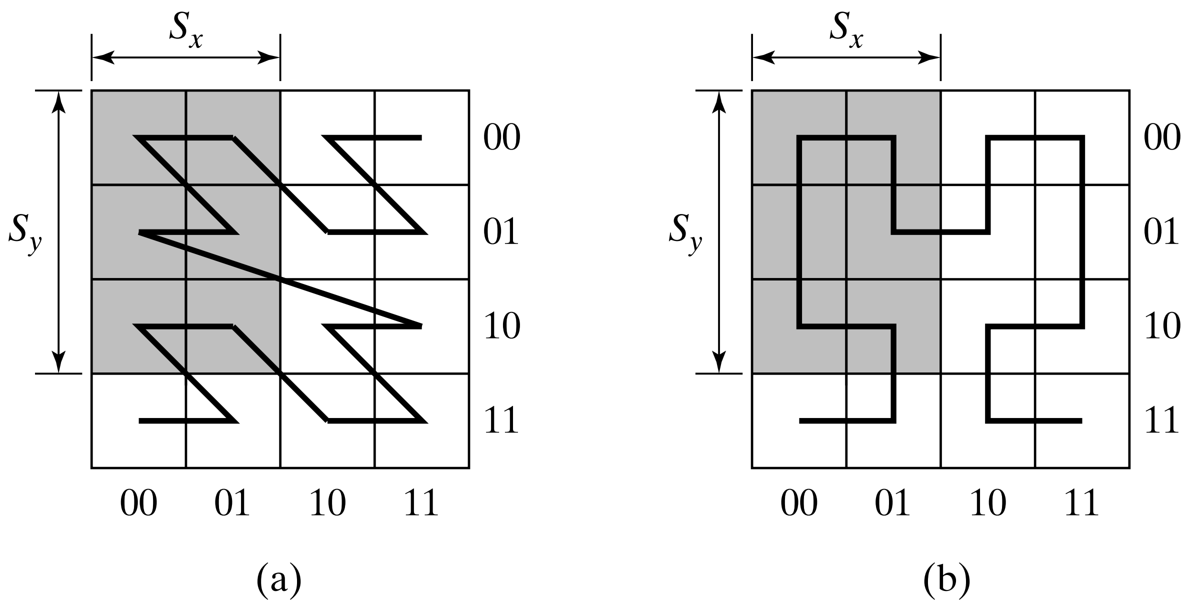
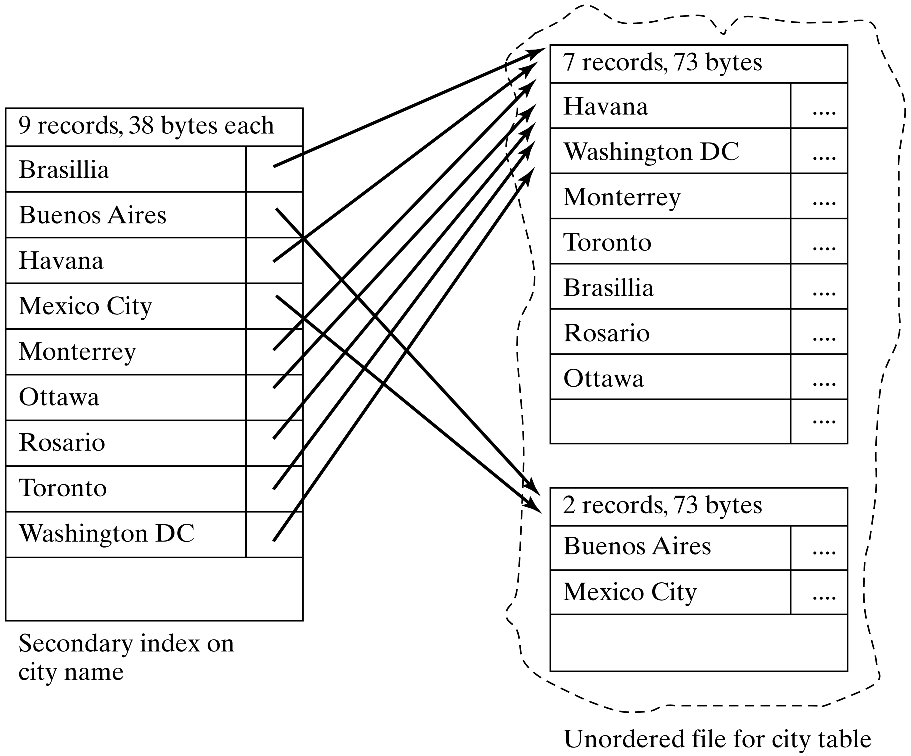


Figure 4.9

What is an Index?

- Concept of an index
  - Auxiliary file to search a data file
  - Example: Figure 4.10
- Index records have
  - Key value
  - Address of relevant data sector
    - see arrows in Figure 4.10
- Index records are ordered
  - find, findnext, insert are fast
- Note assumption of total order
  - On values of indexed attributes

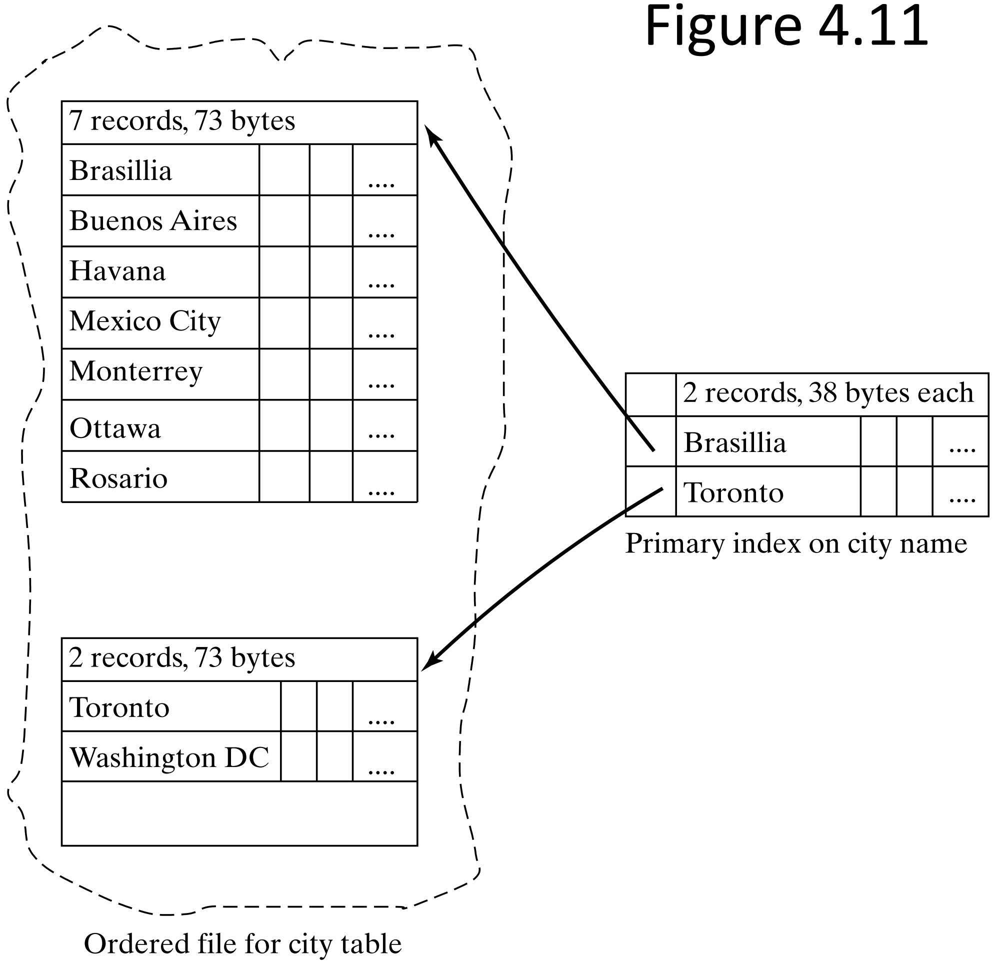
Figure 4.10



Classifying Indexes

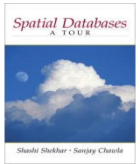
- Classification criteria
  - Data-file-structure
  - Key data type
  - Others
- Secondary index
  - Heap data file
  - 1 index record / data record
  - Example Figure 4.10
- Primary index
  - Data file ordered by indexed attribute
  - 1 index record / data sector
  - Example: Figure 4.11
- Q? A table can have at most one primary index. Why?

Figure 4.11



Attribute Data Types and Indices

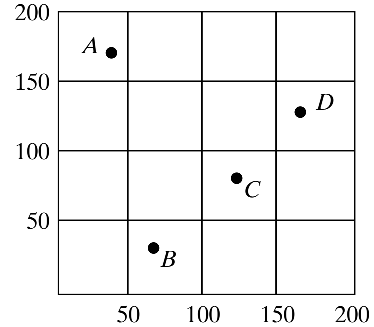
- Index file structure depends on data type of indexed attribute
  - Attributes with total order
    - Example, numbers, points ordered by space filling curves
    - B-tree is a popular index organization
    - See Figure 1.12 (pp.18) and section 1.6.4
  - Spatial objects (e.g. polygons)
    - Spatial organization are more efficient
    - Hundreds of organizations are proposed in literature
    - Two main families are Grid Files and R-trees



Ideas Behind Grid Files

- Basic idea - Divide space into cells by a grid
  - Example: Figure 4.12
  - Example: latitude-longitude, ESRI Arc/SDE
  - Store data in each cell in distinct disk sector
  - Efficient for find, insert, nearest neighbor
  - But may have wastage of disk storage space
    - non-uniform data distribution over space
- Refinement of basic idea into Grid Files
  - Use non-uniform grids (Figure 4.14)
  - Linear scale store row and column boundaries
  - Allow sharing of disk sectors across grid cells
  - See Figure 4.13 on next slide

Figure 4.12



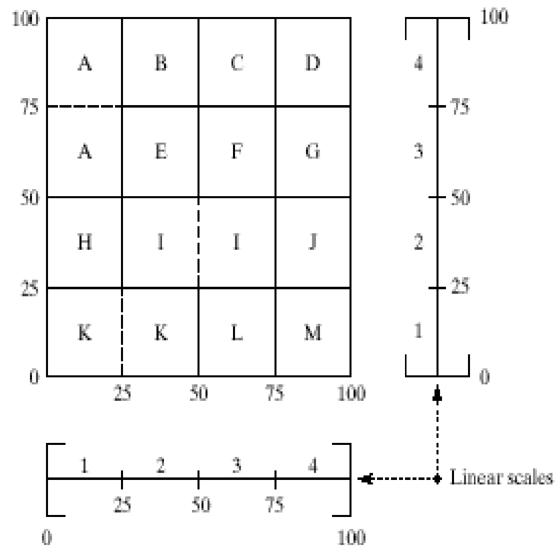


Figure 4.14

Grid Files

- Grid File component
  - Linear scale - row/column boundaries
  - Grid directory: cell --> disk sector address
  - Data sectors on disk
- Operation implementation
  - Scales and grid directory in main memory
  - Steps for find, nearest neighbor
    - search linear scales
    - identify selected grid directory cells
    - retrieve selected disk sectors
- Performance overview
  - Efficient in terms of I/O costs
  - Needs large main memory for grid directory

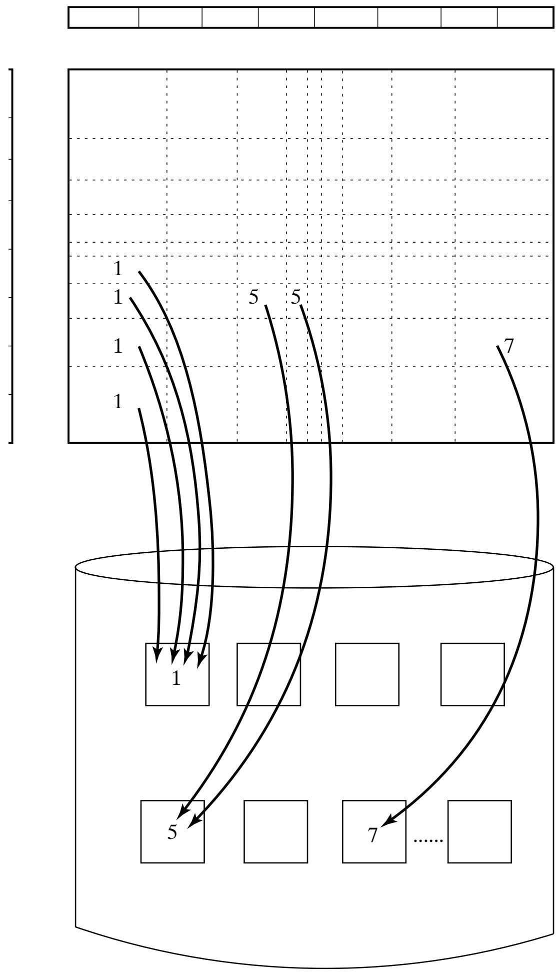


Figure 4.13

R-Tree Family

- Basic Idea
  - Use a hierarchical collection of rectangles to organize spatial data
  - Generalizes B-tree to spatial data sets
- Classifying members of R-tree family
  - Handling of large spatial objects
    - allow rectangles to overlap - R-tree
    - duplicate objects but keep interior node rectangles disjoint - R+tree
  - Selection of rectangles for interior nodes
    - greedy procedures - R-tree, R+tree
    - procedure to minimize coverage, overlap - packed R-tree
  - Other criteria exist
- Scope of our discussion
  - Basics of R-tree and R+tree
  - Focus on concepts not procedures!

Spatial Objects with R-Tree

- Properties of R-trees
  - Balanced
  - Nodes are rectangle
    - child's rectangle within parent's
    - possible overlap among rectangles!
  - Other properties in section 4.2.2
- Implementation of find operation
  - Search root to identify relevant children
  - Search selected children recursively
- Example: find record for rectangle 5
  - Root search identifies child x
  - Search of x identifies children b and c
  - Search of b does not find object 5
  - Search of c find object 5

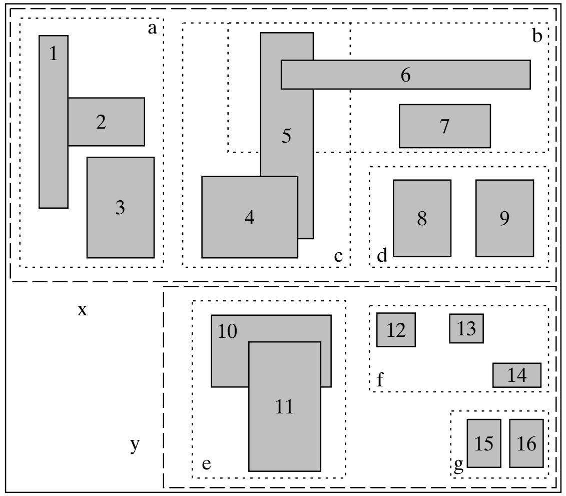
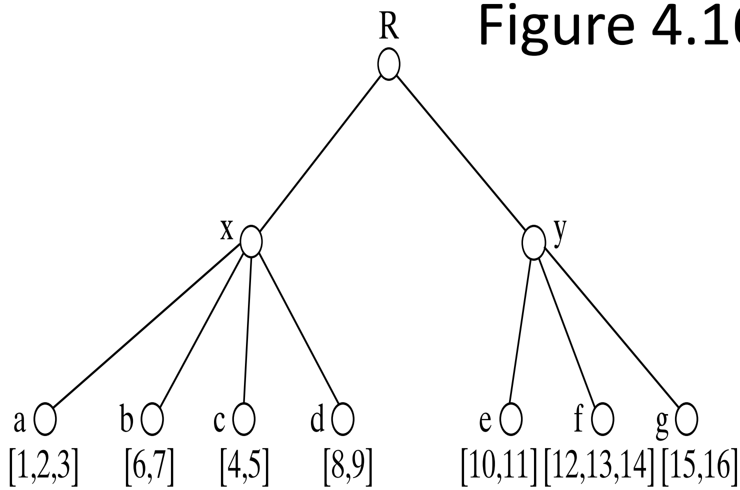


Figure 4.15

Figure 4.16



R+tree

- Properties of R+trees
  - Balanced
  - Interior nodes are rectangle
    - child’s rectangle within parent’s
    - disjoint rectangles
  - Leaf nodes - MOBR of polygons or lines
    - leaf’s rectangle overlaps with parent’s
  - Data objects may be duplicated across leafs
  - Other properties in section 4.2.2
- find operation - same as R-tree
  - But only one child is followed down
- Example: find record for rectangle 5
  - Root search identifies child x
  - Search of x identifies children b and c
  - Search either b or c to find object 5

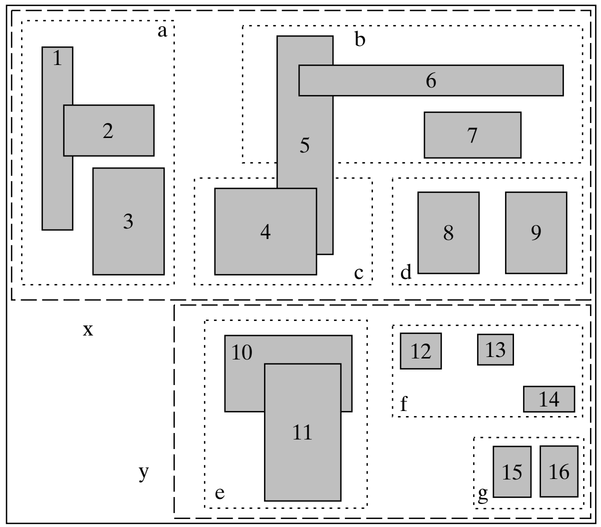


Figure 4.18

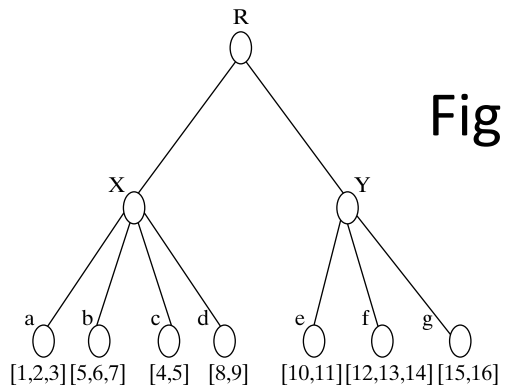


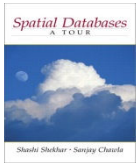
Figure 4.17

Trends

- New developments in physical model
  - Use of intra-object indexes
  - Support for multiple concurrent operations
  - Index to support spatial join operations
- Use of intra-object indexes
  - Motivation: large objects (e.g. polygon boundary of USA has 1000s of edges)
  - Algorithms for OGIS operations (e.g. touch, crosses)
    - often need to check only a few edges of the polygon
    - relevant edges can be identified by spatial index on edges
    - example: Figure 4.19, pp.105, section 4.3.1
  - Uniqueness
    - intra-object index organizes components within a large spatial object
    - traditional index organizes a collection of spatial objects

Trends – Concurrency support

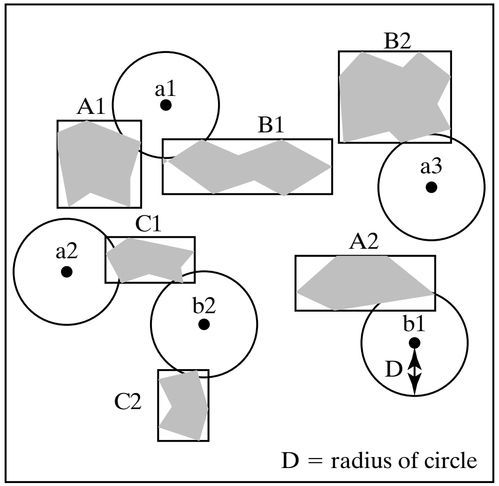
- Why support concurrent operations?
  - SDBMS is shared among many users and applications
  - Simultaneous requests from multiple users on a spatial table
    - serial processing of request is not acceptable for performance
    - concurrent updates and find can provide incorrect results
- Concurrency control idea for R-tree index
  - R-link tree: Add links to chain nodes at each level
  - Use links to ensure correct answer from find operations
  - Use locks on nodes to coordinate conflicting updates
  - Details in section 4.3.2 and Figure 4.20, pp.107



Trends: Join Index

- Spatial join is a common operation. Expensive to compute using traditional indexes
- Spatial join index pre-computes and stores id-pairs of matched rows across tables
- Example in Figure 4.21
- Speeds up computation of spatial join
    - details in section 4.3.3

Figure 4.21



(a) Spatial attribute of R and S

R Relation (Facility Location)

ID	Location (X,Y)	Non-Spatial Data
a1	(7.9, 16.7)	(...)
a2	(3.4, 11.4)	(...)
a3	(19.5, 13.1)	(...)
b1	(18.7, 6.4)	(...)
b2	(9.5, 7.1)	(...)

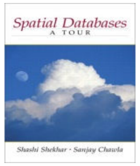
S Relation (Forest-Stand Boundary)

ID	MOBR (X_{LL} Y_{LL} X_{UR} Y_{UR})	Non-Spatial Data
A1	(3, 12.2, 6.6, 16)	(...)
A2	(13.4, 7.7, 19.5, 10)	(...)
B1	(7.6, 12.7, 15, 5.2)	(...)
B2	(15.5, 15, 20.4, 19)	(...)
C1	(5.1, 8.9, 9.1, 10.9)	(...)
C2	(7.5, 2,9.7, 15.1)	(...)

Join-Index

R.ID	S.ID
a1	A1
a1	B1
a2	C1
a3	B2
b1	A2
b2	C1
b2	C2

(b) R and S relation table and join-index



Spatial Join-index Details

Figure 4.22

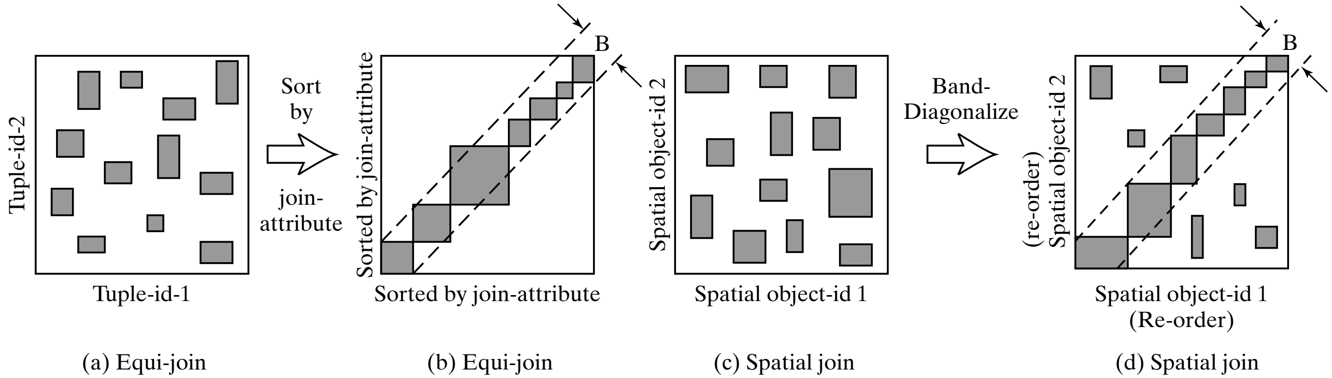
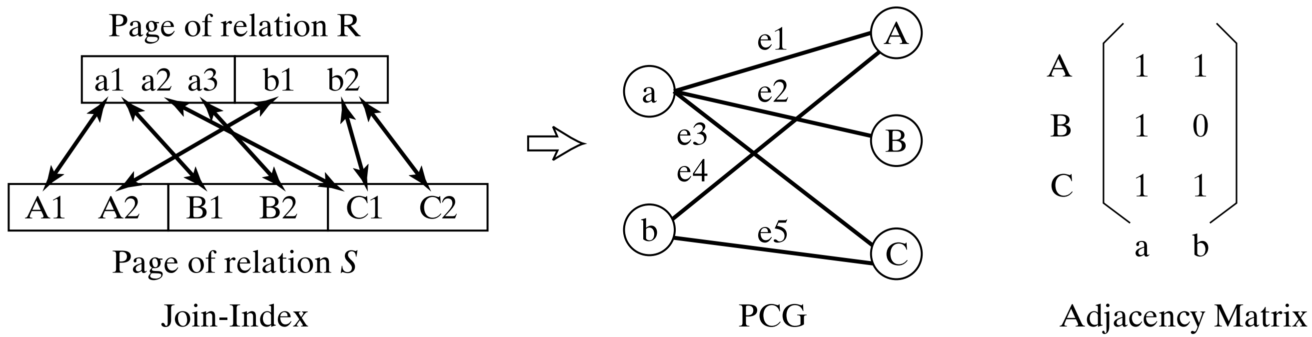


Figure 4.23



Summary

- Physical DM efficiently implements logical DM on computer hardware
  - Physical DM has file-structure, indexes
- Classical methods were designed for data with total ordering
  - Fall short in handling spatial data
  - Because spatial data is multi-dimensional
- Two approaches to support spatial data and queries
  - Reuse classical method
    - use Space-Filling curves to impose a total order on multi-dimensional data
  - Use new methods
    - R-trees, Grid files