Database Management Systems

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CMPUT 391: Spatial Data Management

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Chapter 28 of Textbook

Course Content

- Introduction
- Database Design Theory
- Query Processing and Optimisation
- Concurrency Control
- Data Base Recovery and Security
- Object-Oriented Databases
- Inverted Index for IR
- **Spatial Data Management**
- XML
- Data Warehousing
- Data Mining
- Parallel and Distributed Databases

Objectives of Lecture 8

Spatial Data Management

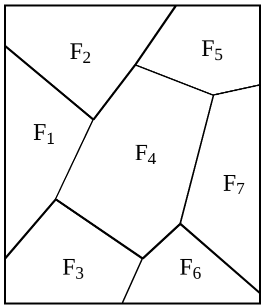
- This lecture will give you a basic understanding of spatial data management
  - What is special about spatial data
  - What are spatial queries
  - How do typical spatial index structures work

Spatial Data Management

- Modeling Spatial Data
- Spatial Queries
- Space-Filling Curves + B-Trees
- R-trees

Relational Representation of Spatial Data

- *Example*: Representation of geometric objects (here: parcels/fields of land) in normalized relations



Parcels

FNr	BNr
F_1	B_1
F_1	B_2
F_1	B_3
F_1	B_4
F_4	B_2
F_4	B_5
F_4	B_6
F_4	B_7
F_4	B_8
F_4	B_9
F_7	B_7
F_7	B_{10}
F_7	B_{11}
F_7	B_{12}
...	...

Borders

BNr	PNr_1	PNr_2
B_1	P_1	P_2
B_2	P_2	P_3
B_3	P_3	P_4
B_4	P_4	P_1
B_5	P_2	P_5
B_6	P_5	P_6
B_7	P_6	P_7
B_8	P_7	P_8
B_9	P_8	P_3
B_{10}	P_6	P_9
B_{11}	P_9	P_{10}
B_{12}	P_{10}	P_7

Points

PNr	X-Coord	Y-Coord
P_1	X_{P1}	Y_{P1}
P_2	X_{P2}	Y_{P2}
P_3	X_{P3}	Y_{P3}
P_4	X_{P4}	Y_{P4}
P_5	X_{P5}	Y_{P5}
P_6	X_{P6}	Y_{P6}
P_7	X_{P7}	Y_{P7}
P_8	X_{P8}	Y_{P8}
P_9	X_{P9}	Y_{P9}
P_{10}	X_{P10}	Y_{P10}

Redundancy free representation requires distribution of the information over 3 tables: *Parcels*, *Borders*, *Points*

Relational Representation of Spatial Data

- For (spatial) queries involving parcels it is necessary to reconstruct the spatial information from the different tables
  - E.g.: if we want to determine if a given point P is inside parcel F_2, we have to find all corner-points of parcel F_2 first

SELECT Points.PNr, X-Coord, Y-Coord
FROM Parcels, Border, Points
WHERE FNr = 'F_2' *AND*
Parcel.BNr = Borders.BNr *AND*
($Borders.PNr_1$ = Points.PNr *OR*
$Borders.PNr_2$ = Points.PNr)

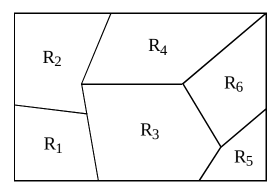
- Even this simple query requires expensive joins of three tables
- Querying the geometry (e.g., P in F_2?) is not directly supported.

Extension of the Relational Model to Support Spatial Data

- Integration of spatial data types and operations into the core of a DBMS (→ object-oriented and object-relational databases)
  - Data types such as *Point*, *Line*, *Polygon*
  - Operations such as *ObjectIntersect*, *RangeQuery*, etc.
- Advantages
  - Natural extension of the relational model and query languages
  - Facilitates design and querying of spatial databases
  - Spatial data types and operations can be supported by spatial index structures and efficient algorithms, implemented in the core of a DBMS
- All major database vendors today implement support for spatial data and operations in their database systems via object-relational extensions

Extension of the Relational Model to Support Spatial Data – Example

Relation: **ForestZones**(Zone: *Polygon*, ForestOfficial: *String*, Area: *Cardinal*)



ForestZones

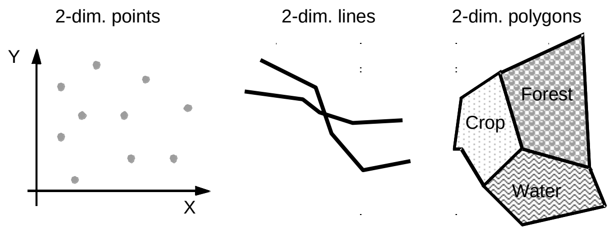
Zone	ForestOfficial	Area (m^2)
R_1	Stevens	3900
R_2	Behrens	4250
R_3	Lee	6700
R_4	Goebel	5400
R_5	Jones	1900
R_6	Kent	4600

- The province decides that a reforestation is necessary in an area described by a polygon S. Find all forest officials affected by this decsion.

```
SELECT   ForestOfficial
FROM     ForestZones
WHERE    ObjectIntersects (S, Zone)
```

Data Types for Spatial Objects

- Spatial objects are described by
  - Spatial Extent
    - *location* and/or *boundary* with respect to a reference point in a coordinate system, which is at least 2-dimensional.
    - Basic object types: *Point*, *Lines*, *Polygon*
  - Other Non-Spatial Attributes
    - Thematic attributes such as height, area, name, land-use, etc.

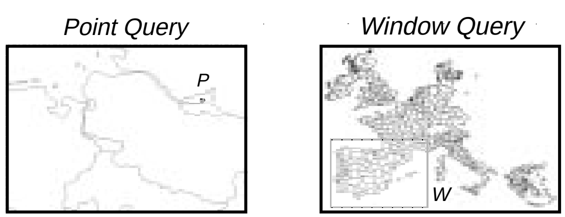


Spatial Data Management

- Modeling Spatial Data
- Spatial Queries
- Space-Filling Curves + B-Trees
- R-trees

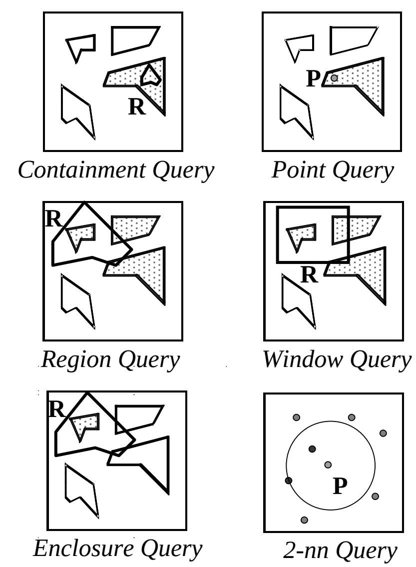
Spatial Query Processing

- DBMS has to support two types of operations
  - Operations to retrieve certain subsets of spatial object from the database
    - "Spatial Queries/Selections", e.g., window query, point query, etc.
  - Operations that perform basic geometric computations and tests
    - E.g., point in polygon test, intersection of two polygons etc.
- Spatial selections, e.g. in geographic information systems, are often supported by an interactive graphical user interface



Basic Spatial Queries

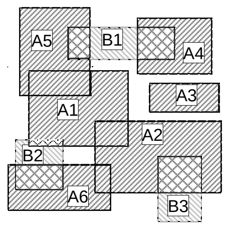
- ***Containment Query***: Given a spatial object R, find all objects that completely contain R. If R is a Point: ***Point Query***
- ***Region Query***: Given a region R (polygon or circle), find all spatial objects that intersect with R. If R is a rectangle: ***Window Query***
- ***Enclosure Query***: Given a polygon region R, find all objects that are completely contained in R
- ***K-Nearest Neighbor Query***: Given an object P, find the k objects that are closest to P (typically for points)



Basic Spatial Queries – Spatial Join

- Given two sets of spatial objects (typically minimum bounding rectangles)
  - $S_1 = \{R_1, R_2, \ldots, R_m\}$ and $S_2 = \{R'_1, R'_2, \ldots, R'_n\}$
- Spatial Join: Compute all pairs of objects (R, R') such that
  - $R \in S_1, R' \in S_2$,
  - and R intersects R' ($R \cap R' \neq \emptyset$)
  - Spatial predicates other that intersection are also possible, e.g. all pairs of objects that are within a certain distance from each other

$\{A1, \ldots, A6\} \bowtie \{B1, \ldots, B3\}$

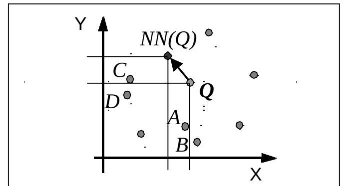


Spatial-Join

Answer Set
(A5, B1)
(A4, B1)
(A1, B2)
(A6, B2)
(A2, B3)

Index Support for Spatial Queries

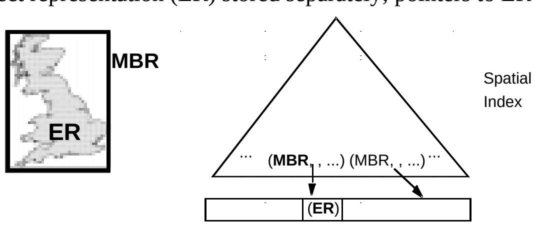
- Conventional index structures such as B-trees are not designed to support spatial queries
  - Group objects only along one dimension
  - Do not preserve spatial proximity
    - E.g. nearest neighbor query:
      Nearest neighbor of Q is typically not the nearest neighbor in any single dimension



A and B closer in the X dimension;
C and D closer in the Y dimension.

Index Support for Spatial Queries

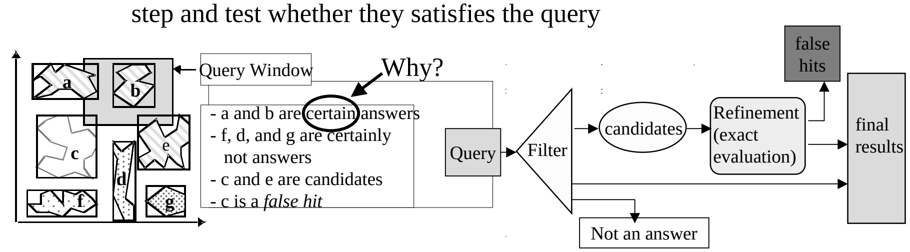
- Spatial index structures try to preserve spatial proximity
  - Group objects that are close to each other on the same data page
  - Problem: the number of bytes to store extended spatial objects (lines, polygons) varies
  - Solution:
    - Store ***Approximations*** of spatial objects in the index structure, typically axis-parallel minimum bounding rectangles (MBR)
    - Exact object representation (ER) stored separately; pointers to ER in the index



Query Processing Using Approximations

Two-Step Procedure

1. Filter Step:
   - Use the index to find all approximations that satisfy the query
   - Some objects already satisfy the query based on the approximation, others have to be checked in the refinement step → Candidate Set
2. Refinement Step:
   - Load the exact object representations for candidates left after the filter step and test whether they satisfies the query



Spatial Data Management

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- Space-Filling Curves + B-Trees
- R-trees

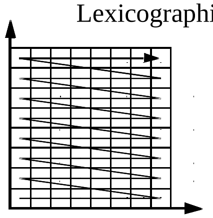
Embedding of the 2-dimensional space into a 1 dimensional space

- Basic Idea:
  - The data space is partitioned into rectangular cells.
  - Use a space filling curve to assign cell numbers to the cells (define a linear order on the cells)
    - The curve should preserve spatial proximity as good as possible
    - Cell numbers should be easy to compute
  - Objects are approximated by cells.
  - Store the cell numbers for objects in a conventional index structure with respect to the linear order

21	23	29	31	53	55	61	63
20	22	28	30	52	54	60	62
17	19	25	27	49	51	57	59
16	18	24	26	48	50	56	58
5	7	13	15	37	39	45	47
4	6	12	14	36	38	44	46
1	3	9	11	33	35	41	43
0	2	8	10	32	34	40	42

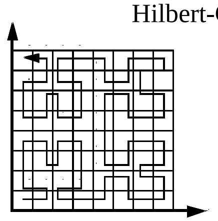
Space Filling Curves

Lexicographic Order



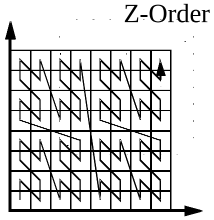
56	57	58	59	60	61	62	63
48	49	50	51	52	53	54	55
40	41	42	43	44	45	46	47
32	33	34	35	36	37	38	39
24	25	26	27	28	29	30	31
16	17	18	19	20	21	22	23
8	9	10	11	12	13	14	15
0	1	2	3	4	5	6	7

Hilbert-Curve



63	62	49	48	47	44	43	42
60	61	50	51	46	45	40	41
59	56	55	52	33	34	39	38
58	57	54	53	32	35	36	37
5	6	9	10	31	28	27	26
4	7	8	11	30	29	24	25
3	2	13	12	17	18	23	22
0	1	14	15	16	19	20	21

Z-Order



21	23	29	31	53	55	61	63
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4	6	12	14	36	38	44	46
1	3	9	11	33	35	41	43
0	2	8	10	32	34	40	42

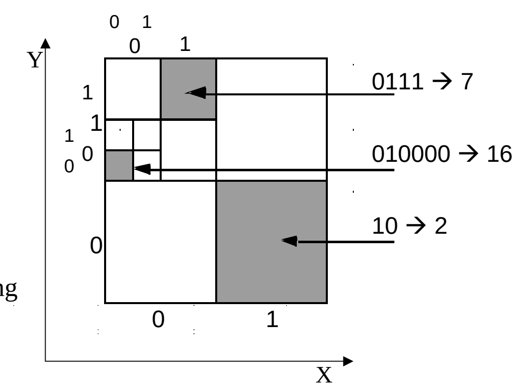
- Z-Order preserves spatial proximity relatively good
- Z-Order is easy to compute

Z-Order – Z-Values

- Coding of Cells
  - Partition the data space recursively into two halves
  - Alternate X and Y dimension
  - Left/bottom → 0
  - Right/top → 1

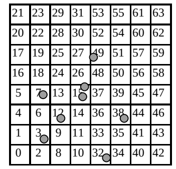
  - **Z-Value: (*c*, *l*)**
    c = decimal value of the bit string
    l = level (number of bits)

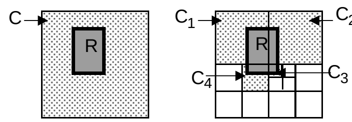
    if all cells are on the same level, then *l* can be omitted



Z-Order – Representation of Spatial Objects

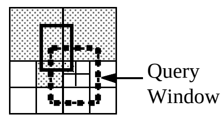
- For Points
  - Use a fixed a resolution of the space in both dimensions, i.e., each cell has the same size
  - Each point is then approximated by one cell
- For extended spatial object
  - minimum enclosing cell
    - Problems with cells that intersect the first partitions already
  - improvement: use several cells
    - Better approximation of the objects
    - Redundant storage
    - Redundant retrieval in spatial queries





Coding of R by one cell

Coding of R by several cells



Query returns the same answer several times

Z-Order – Mapping to a B^+-Tree

- Linear Order for Z-values to store them in a B^+-tree:

Let (c_1, l_1) and (c_2, l_2) be two Z-Values and let $l = \min\{l_1, l_2\}$.

The order relation $\leq_Z$ (that defines a linear order on Z-values) is then defined by

$$(c_1, l_1) \leq_Z (c_2, l_2) \text{ iff } (c_1 \text{ div } 2^{(l_1 - l)}) \leq (c_2 \text{ div } 2^{(l_2 - l)})$$

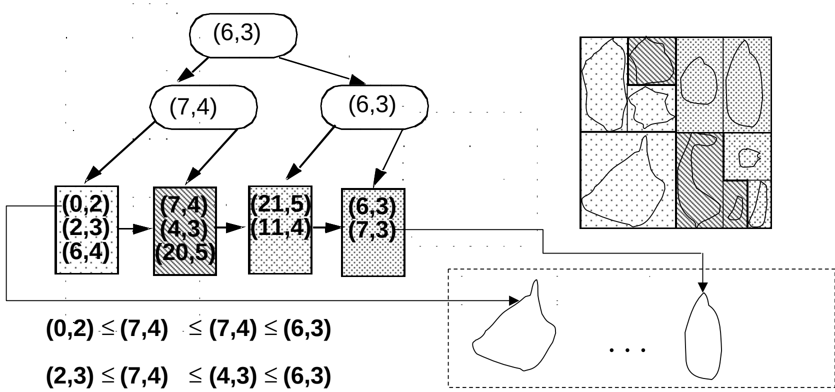
Examples:

$(1,2) \leq_Z (3,2)$,

$(3,4) \leq_Z (3,2)$,

$(1,2) \leq_Z (10,4)$

Mapping to a B^+-Tree - Example



(0,2) ≤ (7,4) ≤ (7,4) ≤ (6,3)

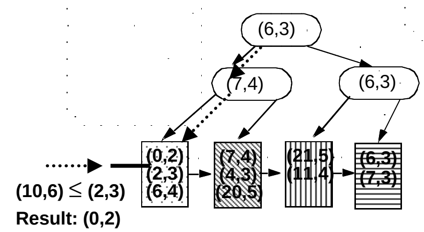
(2,3) ≤ (7,4) ≤ (4,3) ≤ (6,3)

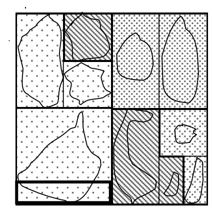
(6,4) ≤ (7,4) ≤ (20,5) ≤ (6,3)

Exact representations stored in a different location

Mapping to a B^+-Tree – Window Query

- Window Query → Range Query in the B+-tree
  - find all entries (Z-Values) in the range $[l, u]$ where
    - l = smallest Z-Value of the window (bottom left corner)
    - u = largest Z-Value of the window (top right corner)
    - l and u are computed with respect to the maximum resolution/length of the Z-values in the tree (here: 6)





Window: Min = (0,6), Max = (10,6)

Spatial Data Management

- Modeling Spatial Data
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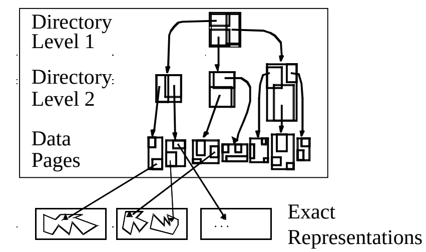
- Space-Filling Curves + B-Trees
- R-trees

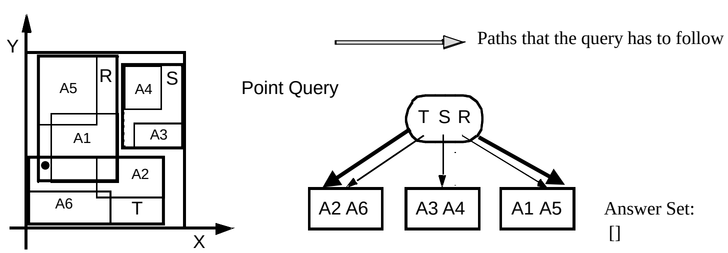
The R-Tree – Properties

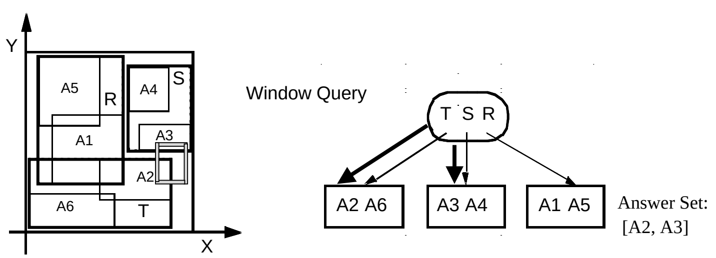
- Balanced Tree designed to organize rectangles [Gut 84].
- Each page contains between *m* and *M* entries.
- Data page entries are of the form (*MBR*, *PointerToExactRepr*).
  - MBR is a minimum bounding rectangle of a spatial object, which PointerToExactRepr is pointing to
- Directory page entries are of the form (*MBR*, *PointerToSubtree*).
  - *MBR* is the minimum bounding rectangle of all entries in the subtree, which *PointerToSubtree* is pointing to.
- Rectangles can overlap
- The height *h* of an R-Tree for *N* spatial objects:

$$h \leq \lceil \log_m N \rceil + 1$$



The R-Tree – Queries





The R-Tree – Queries

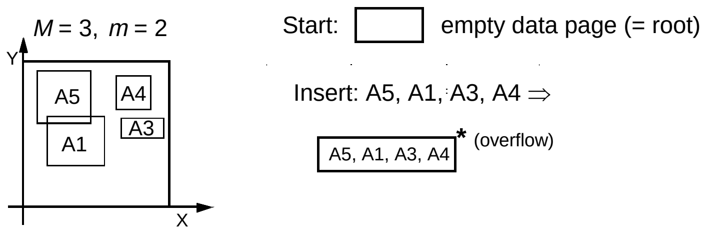
```
PointQuery (Page, Point);
 FOR ALL Entry ∈ Page DO
   IF Point IN Entry.MBR THEN
     IF Page = DataPage THEN
       PointInPolygonTest (load(Entry.ExactRepr), Point)
     ELSE
       PointQuery (Entry.Subtree, Point);
```

First call: Page = Root of the R-tree

```
Window Query (Page, Window);
 FOR ALL Entry ∈ Page DO
   IF Window INTERSECTS Entry.MBR THEN
     IF Page = DataPage THEN
       Intersection (load(Entry.ExactRepr), Window)
     ELSE
       WindowQuery (Entry.Subtree, Window);
```

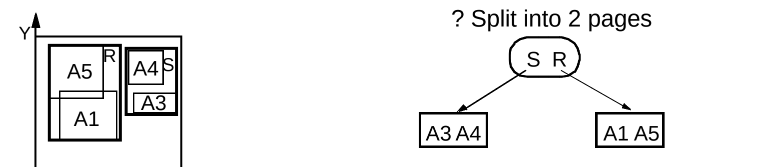
R-Tree Construction – Optimization Goals

- Overlap between the MBRs
  - ⇒ spatial queries have to follow several paths
  - ⇒ try to minimize overlap
- Empty space in MBR
  - ⇒ spatial queries may have to follow irrelevant paths
  - ⇒ try to minimize area and empty space in MBRs



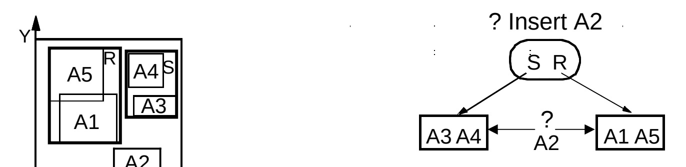
R-Tree Construction – Important Issues

- Split Strategy



How to divide a set of rectangles into 2 sets?

- Insertion Strategy



Where to insert a new rectangle?

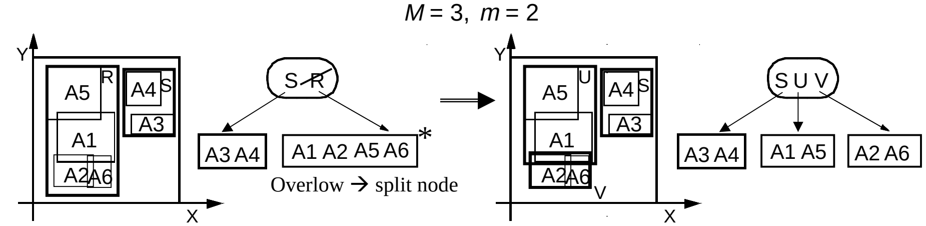
R-Tree Construction – Insertion Strategies

- Dynamic construction by insertion of rectangles *R*
  - Searching for the data page into which *R* will be inserted, traverses the tree from the root to a data page.
  - When considering entries of a directory page *P*, 3 cases can occur:
    1. *R* falls into exactly one *Entry.MBR*
       → follow *Entry.Subtree*
    2. *R* falls into the MBR of more than one entry e_1 , ... , e_n
       → follow E_i*.Subtree* for entry e_i with the smallest area of e_i*.MBR*.
    3. *R* does not fall into an *Entry.MBR* of the current page
       → check the increase in area of the *MBR* for each entry when enlarging the *MBR* to enclose *R*. Choose *Entry* with the minimum increase in area (if this entry is not unique, choose the one with the smallest area); enlarge *Entry.MBR* and follow *Entry.Subtree*
- Construction by "bulk-loading" the rectangles
  - Sort the rectangles, e.g., using Z-Order
  - Create the R-tree "bottom-up"

R-Tree Construction – Split

- Insertion will eventually lead to an overflow of a data page
  - The parent entry for that page is deleted.
  - The page is split into 2 new pages - according to a *split strategy*
  - 2 new entries pointing to the newly created pages are inserted into the parent page.
  - A now possible overflow in the parent page is handled recursively in a similar way; if the root has to be split, a new root is created to contain the entries pointing to the newly created pages.

M = 3, *m* = 2

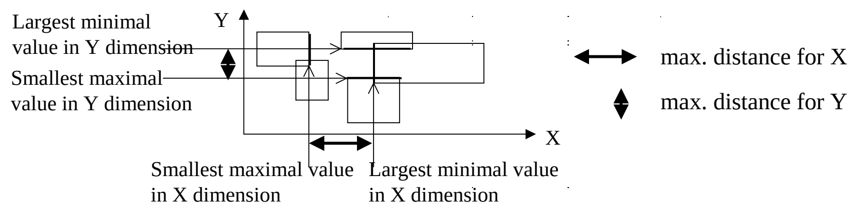


R-Tree Construction – Splitting Strategies

- Overflow of node K with $|K| = M+1$ entries → Distribution of the entries into two new nodes K_1 and K_2 such that $|K_1| \geq m$ and $|K_2| \geq m$
- *Exhaustive algorithm*:
  - Searching for the “best” split in the set of all possible splits is too expensive ($O(2^M)$ possibilities!)
- *Quadratic algorithm*:
  - Choose the pair of rectangles R_1 and R_2 that have the largest value $d(R_1, R_2)$ for empty space in an MBR, which covers both R_1 und R_2.
    $d(R_1, R_2) := \text{Area}(\text{MBR}(R_1 \cup R_2)) - (\text{Area}(R_1) + \text{Area}(R_2))$
  - Set $K_1 := \{R_1\}$ and $K_2 := \{R_2\}$
  - Repeat until STOP
    - if all R_i are assigned: STOP
    - if all remaining R_i are needed to fill the smaller node to guarantee minimal occupancy m: assign them to the smaller node and STOP
    - else: choose the next R_i and assign it to the node that will have the smallest increase in area of the MBR by the assignment. If not unique: choose the K_i that covers the smaller area (if still not unique: the one with less entries).

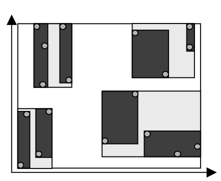
R-Tree Construction – Splitting Strategies

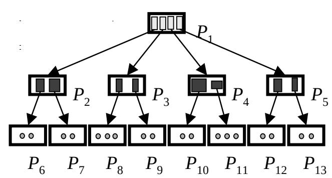
- *Linear algorithm*:
  - Same as the quadratic algorithm, except for the choice of the initial pair: Choose the pair with the largest distance.
    - For each dimension determine the rectangle with the largest minimal value and the rectangle with the smallest maximal value (the difference is the *maximal distance/separation*).
    - Normalize the maximal distance of each dimension by dividing by the sum of the extensions of the rectangles in this dimension
    - Choose the pair of rectangles that has the greatest normalized distance. Set $K_1 := \{R_1\}$ and $K_2 := \{R_2\}$.



R-Trees – Variants

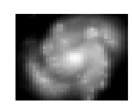
- Many variants of R-trees exist,
  - e.g., the R*-tree, X-tree for higher dimensional point data, …
  - For further information see http://www.cs.umd.edu/~hjs/rtrees/index.html (includes an interactive demo)
- R-trees are also efficient index structures for point data since points can be modeled as “degenerated” rectangles
  - Multi-dimensional points, where a distance function between the points is defined play an important role for similarity search in so-called “feature” or “multi-media” databases.



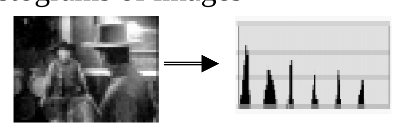


Examples of Feature Databases

- Measurements for celestial objects (e.g., intensity of emission in different wavelengths)



- Color histograms of images



- Documents, shape descriptors, …

n d-dimensional feature vectors
$(o1_1, o1_2, \ldots, o1_d)$
$(o2_1, o2_2, \ldots, o2_d)$
. . .
$(on_1, on_2, \ldots, on_d)$

Feature Databases and Similarity Queries

- Objects + Metric Distance Function
  - The distance function measures (dis)similarity between objects
- Basic types of similarity queries
  - range queries with range ε
    - Retrieves all objects which are similar to the query object up to a certain degree ε
  - *k*-nearest neighbor queries
    - Retrieves *k* most similar objects to the query