# Database Management Systems

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**CMPUT 391: Spatial Data Management**

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Chapter 26 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 ?

**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

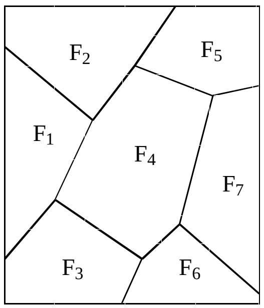


# Spatial Data Management

- 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.



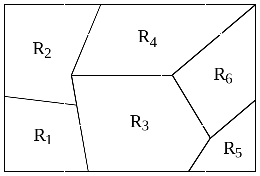
# Extension of the Relational Model to Support Spatial Data

- 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**

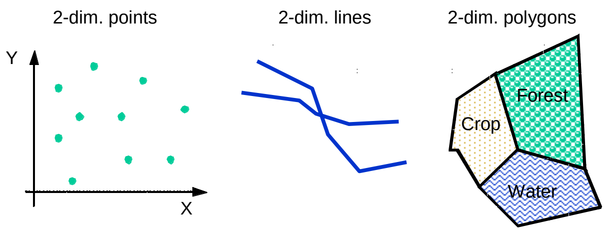
| Zone | ForestOfficial | Area ($m^2$) |
|---|---|---|
| $R_1$ | Stevens | 3900 |
| $R_2$ | Behrens | 4250 |
| $R_3$ | Lee | 6700 |
| $R_4$ | Goebel | 5400 |
| $R_5$ | Jones | 1900 |
| $R_6$ | Kent | 4600 |

- 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

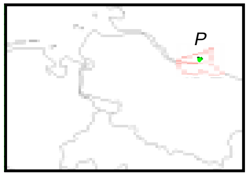
- Modeling Spatial Data
- Spatial Queries
- Space-Filling Curves + B-Trees
- R-trees



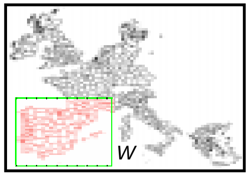
# Spatial Query Processing

- 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

*Point Query*



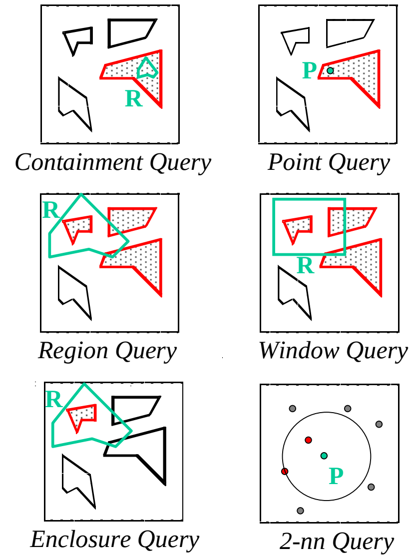

*Window Query*






# Basic Spatial Queries

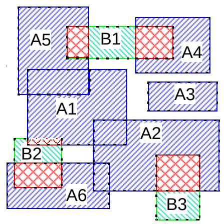
- ***Containment Query***: Given a spatial object R, find all objects that completely contain R. If R is a Point: ***Point Query***
- ***Region Query***: Given a region R (polygon or circle), find all spatial objects that intersect with R. If R is a rectangle: ***Window Query***
- ***Enclosure Query***: 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

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



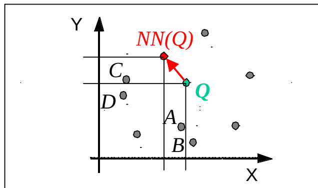

Answer Set
(A5, B1)
(A4, B1)
(A1, B2)
(A6, B2)
(A2, B3)

*Spatial-Join*



# 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

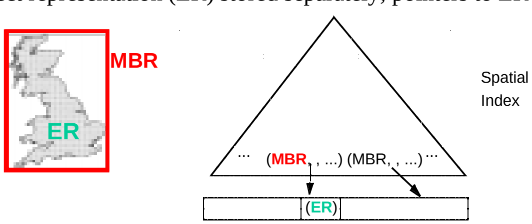



A and B closer in the X dimension;
C and D closer in the Y dimension.



# 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

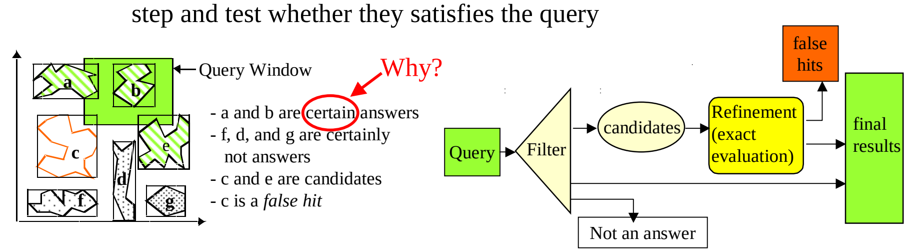





# Query Processing Using Approximations

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

- Modeling Spatial Data
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- R-trees



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

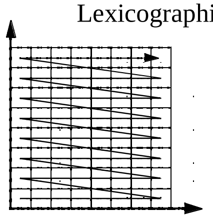
- Basic Idea:
  - The data space is partitioned into rectangular cells.
  - Use a space filling curve to assign cell numbers to the cells (define a linear order on the cells)
    - The curve should preserve spatial proximity as good as possible
    - Cell numbers should be easy to compute
  - Objects 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 |



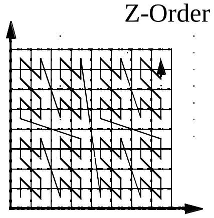
# Space Filling Curves

Lexicographic Order



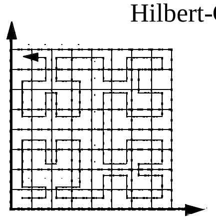
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |
| 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 |
| 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23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

Z-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 |

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

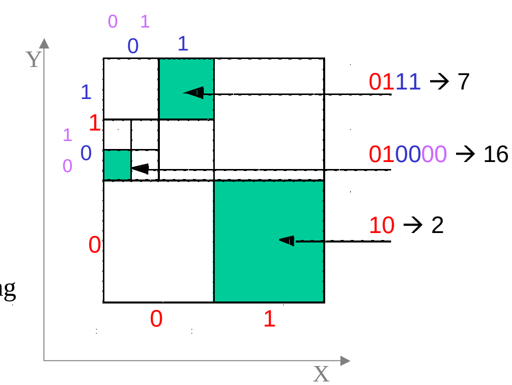


# Z-Order – Z-Values

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

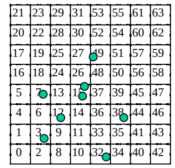
  - **Z-Value: (*c*, *l*)**
    ***c*** = decimal value of the bit string
    ***l*** = level (number of bits)

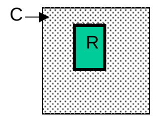
    if all cells are on the same level, then *l* can be omitted



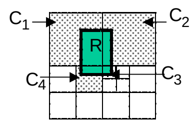
# Z-Order – Representation of Spatial Objects

- 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

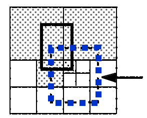



Coding of R by one cell




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

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

*Examples*:

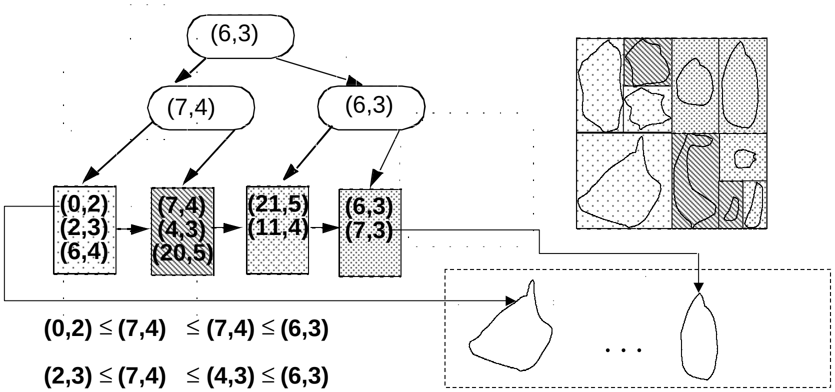
$(1,2) \le_Z (3,2)$,

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

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



# Mapping to a B$^+$-Tree - Example




**(0,2) ≤ (7,4) ≤ (7,4) ≤ (6,3)**

**(2,3) ≤ (7,4) ≤ (4,3) ≤ (6,3)**

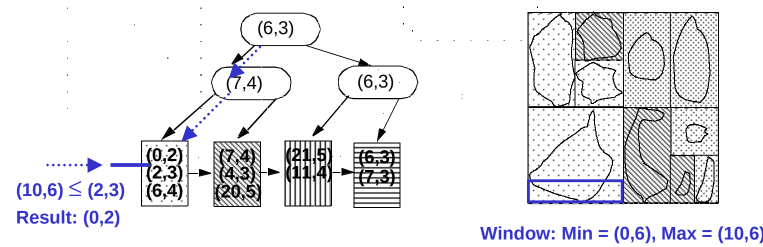
**(6,4) ≤ (7,4) ≤ (20,5) ≤ (6,3)**

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)



# Spatial Data Management

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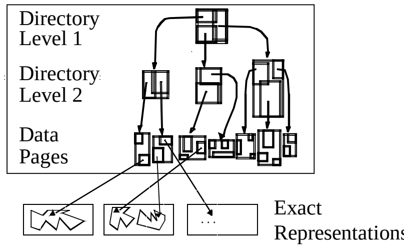
- R-trees



# The R-Tree – Properties

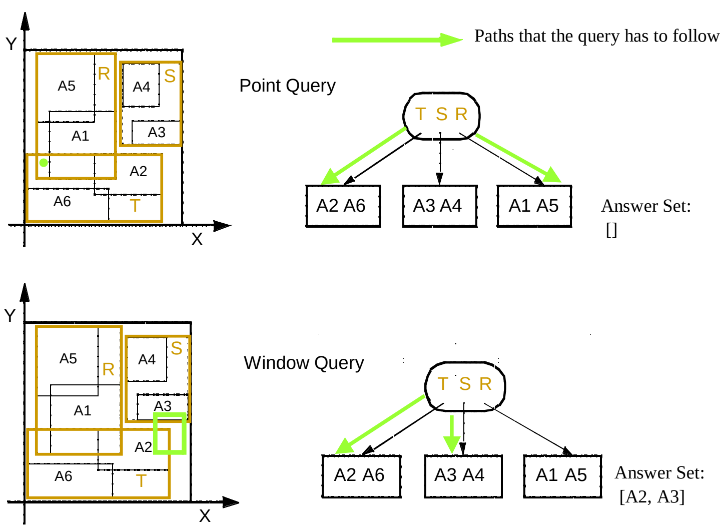
- Balanced Tree designed to organize rectangles [Gut 84].
- Each page contains between *m* and *M* entries.
- Data page entries are of the form (*MBR*, *PointerToExactRepr*).
  - MBR is a minimum bounding rectangle of a spatial object, which PointerToExactRepr is pointing to
- Directory page entries 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

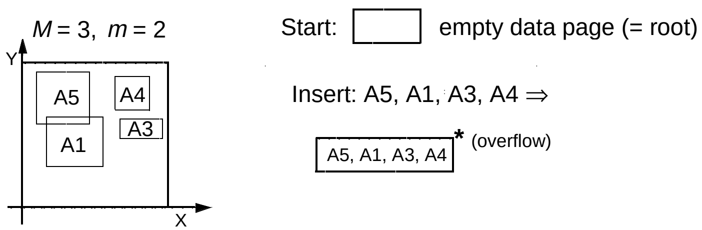
**PointQuery** (Page, Point);
FOR ALL Entry ∈ Page DO
IF Point IN Entry.MBR THEN
IF Page = DataPage THEN
PointInPolygonTest (load(Entry.ExactRepr), Point)
ELSE
PointQuery (Entry.Subtree, Point);

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

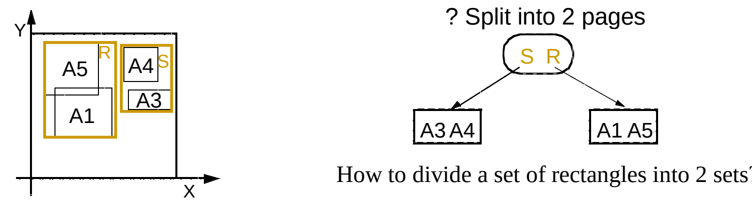
- Overlap between the MBRs
  - ⇒ spatial queries have to follow several paths
  - ⇒ try to minimize overlap
- Empty space in MBR
  - ⇒ spatial queries may have to follow irrelevant paths
  - ⇒ try to minimize area and empty space in MBRs





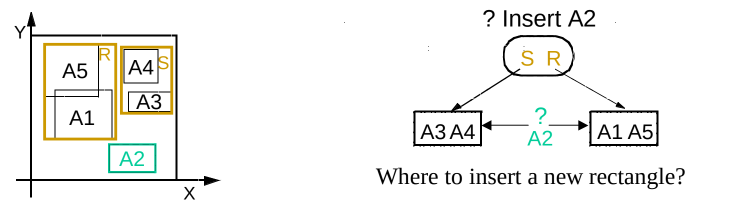

# R-Tree Construction – Important Issues

- 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

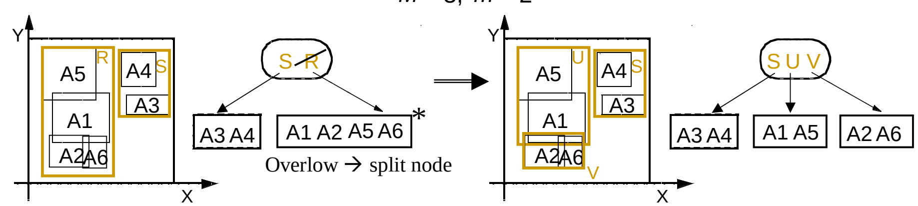
- Dynamic construction by insertion of rectangles *R*
  - Searching for the data page into which *R* will be inserted, traverses the tree from the root to a data page.
  - When considering entries of a directory page *P*, 3 cases can occur:
    1. *R* falls into exactly one *Entry.MBR*
       → follow *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



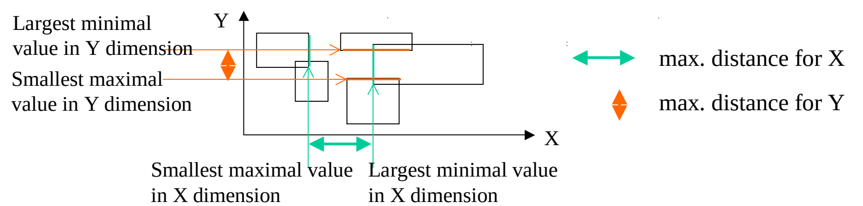
# R-Tree Construction – Splitting Strategies

- 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 two 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

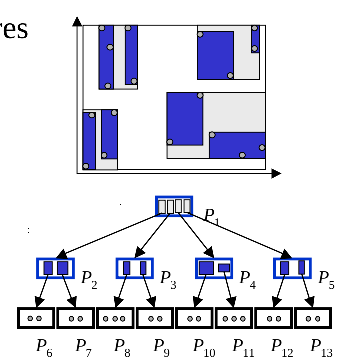
- *Linear algorithm*:
  - Same as the quadratic algorithm, except for the choice of the initial pair: Choose the pair with the largest distance.
    - For each dimension determine the rectangle with the largest minimal value and the rectangle with the smallest maximal value (the difference is the *maximal 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

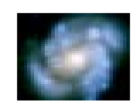
- Many variants of R-trees exist,
  - e.g., the R*-tree, X-tree for higher dimensional point data, …
  - For further information see http://www.cs.umd.edu/~hjs/rtrees/index.html (includes an interactive demo)
- R-trees are also efficient index structures for point data since points can be modeled as "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.



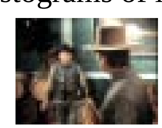


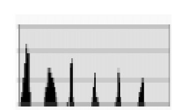

# Examples of Feature Databases

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

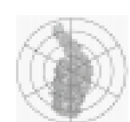


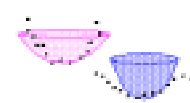
- Color histograms of images





- 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