



DCGI

DEPARTMENT OF COMPUTER GRAPHICS AND INTERACTION

GEOMETRIC SEARCHING PART 2: RANGE SEARCH

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<https://cw.felk.cvut.cz/doku.php/courses/a4m39vg/start>

Based on [Berg] and [Mount]

Version from 17.1.2016

Range search

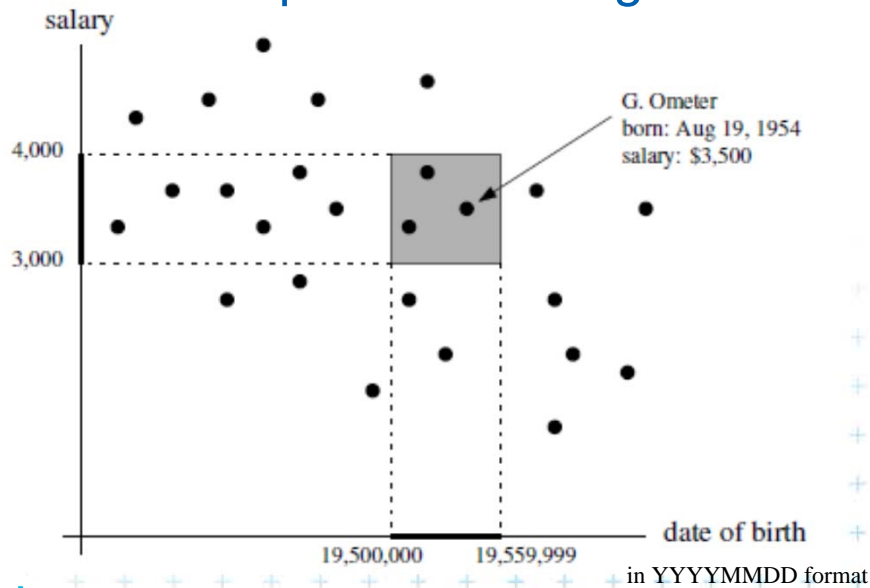
- Orthogonal range searching
- Canonical subsets
- 1D range tree
- Kd-tree
- 2D-nD Range tree
 - With fractional cascading (Layered tree)



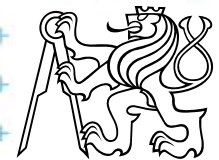
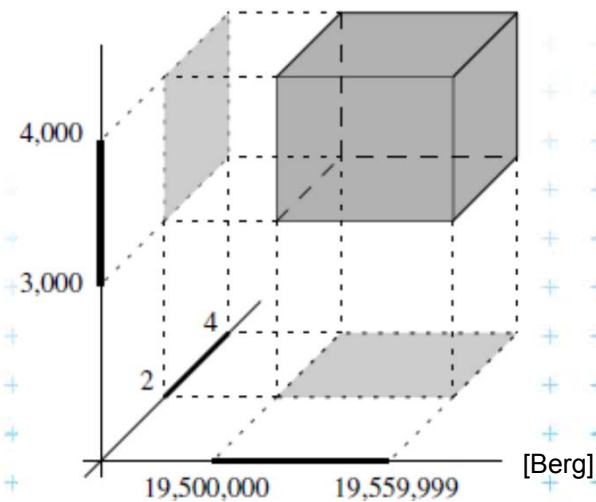
Orthogonal range searching

- Given a set of points P , find the points in the region Q
 - Search space: a set of **points P (somehow represented)**
 - Query: **intervals Q (axis parallel rectangle)**
 - Answer: **points** contained in Q
- Example: Databases (records->points)
 - Find the people with given range of salary, date of birth, kids, ...

2D: axis parallel rectangle



3D: axis parallel box



Orthogonal range searching

- Query region = axis parallel rectangle
 - nDimensional search can be decomposed into set of 1D searches (separable)



Other range searching variants

- Search space S : set of
 - line segments,
 - rectangles, ...
- Query region Q : any other region
 - disc,
 - polygon,
 - halfspace, ...
- Answer: subset of S laying in Q
- We concentrate on points in orthogonal ranges



How to represent the search space?

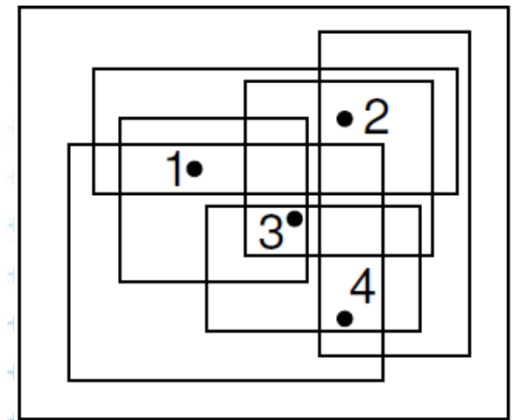
Basic idea:

- Not all possible combination can be in the output (not the whole power set)
- => Represent only the “selectable” things (a well selected subset → one of the canonical subsets)



Subsets selectable by given range class

- The number of subsets that can be selected by simple ranges Q is limited
- It is usually much smaller than the power set of P
 - **Power set of P** where $P = \{1,2,3,4\}$ (potenční množina) is $\{\{\}, \{1\}, \{2\}, \{3\}, \{4\}, \{1,2\}, \{1,3\}, \{1,4\}, \{2,3\}, \dots, \{2,3,4\}, \{1,2,3,4\}\} \dots O(2^n)$
i.e. set of all possible subsets
 - Simple rectangular queries are limited
 - Defined by max 4 points along 4 sides $\Rightarrow O(n^4)$ of $O(2^n)$ power set
 - Moreover – not all sets can be formed by \square query Q
e.g. sets $\{1,4\}$ and $\{1,2,4\}$ cannot be formed



[Mount]



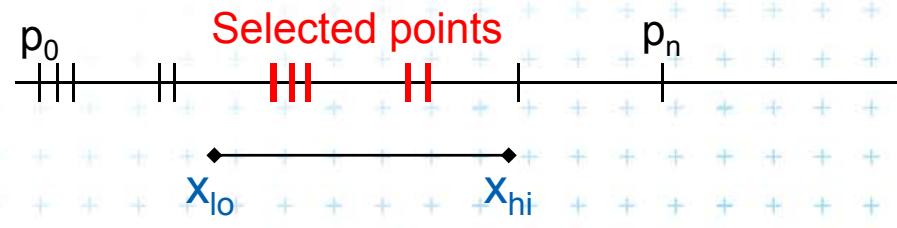
Canonical subsets S_i

- Search space $S=(P,Q)$ represented as a collection of canonical subsets $\{S_1, S_2, \dots, S_k\}$, each $S_i \subseteq S$,
 - S_i may overlap each other (elements can be multiple times there)
 - Any set can be represented as **disjoint union** disjunktní sjednocení of canonical subsets S_i each element knows from which subset it came
 - Elements of disjoint union are ordered pairs (x, i) (every element x with index i of the subset S_i)
- S_i may be selected in many ways
 - from n singletons $\{p_i\}$... $O(n)$
 - to power set of P ... $O(2^n)$
 - Good DS balances between total number of canonical subsets and number of CS needed to answer the query



1D range queries (interval queries)

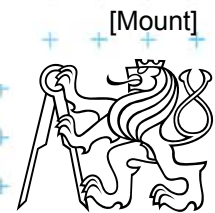
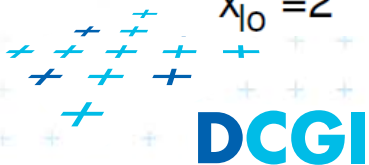
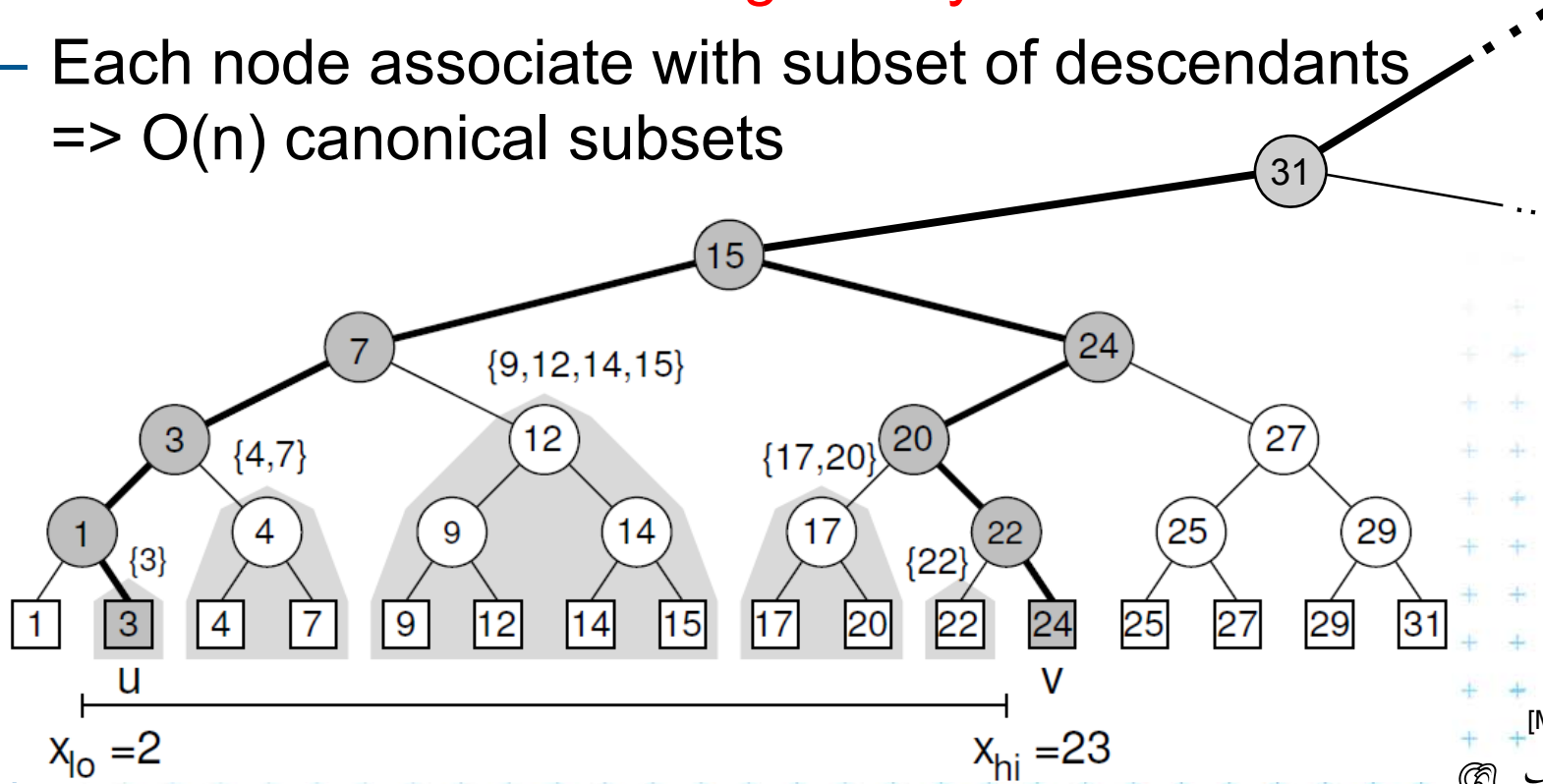
- Query: Search the interval $[x_{lo}, x_{hi}]$
- Search space: Points $P = \{p_1, p_2, \dots, p_n\}$ on the line
 - a) Binary search in an **array**
 - Simple, but
 - not generalize to any higher dimensions
 - b) Balanced **binary search tree**
 - 1D range tree
 - maintains canonical subsets
 - generalize to higher dimensions



1D range tree definition

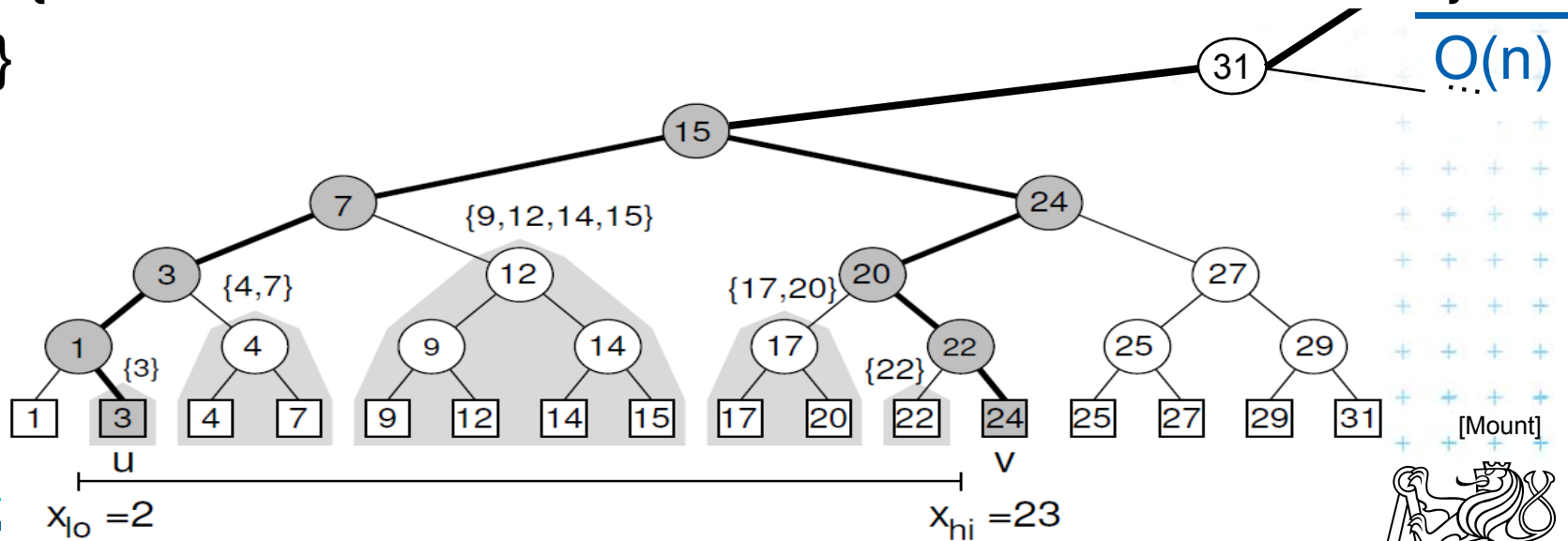
- Balanced binary search tree

- leaves – sorted points
- inner node label – **the largest key in its left child**
- Each node associate with subset of descendants
=> $O(n)$ canonical subsets



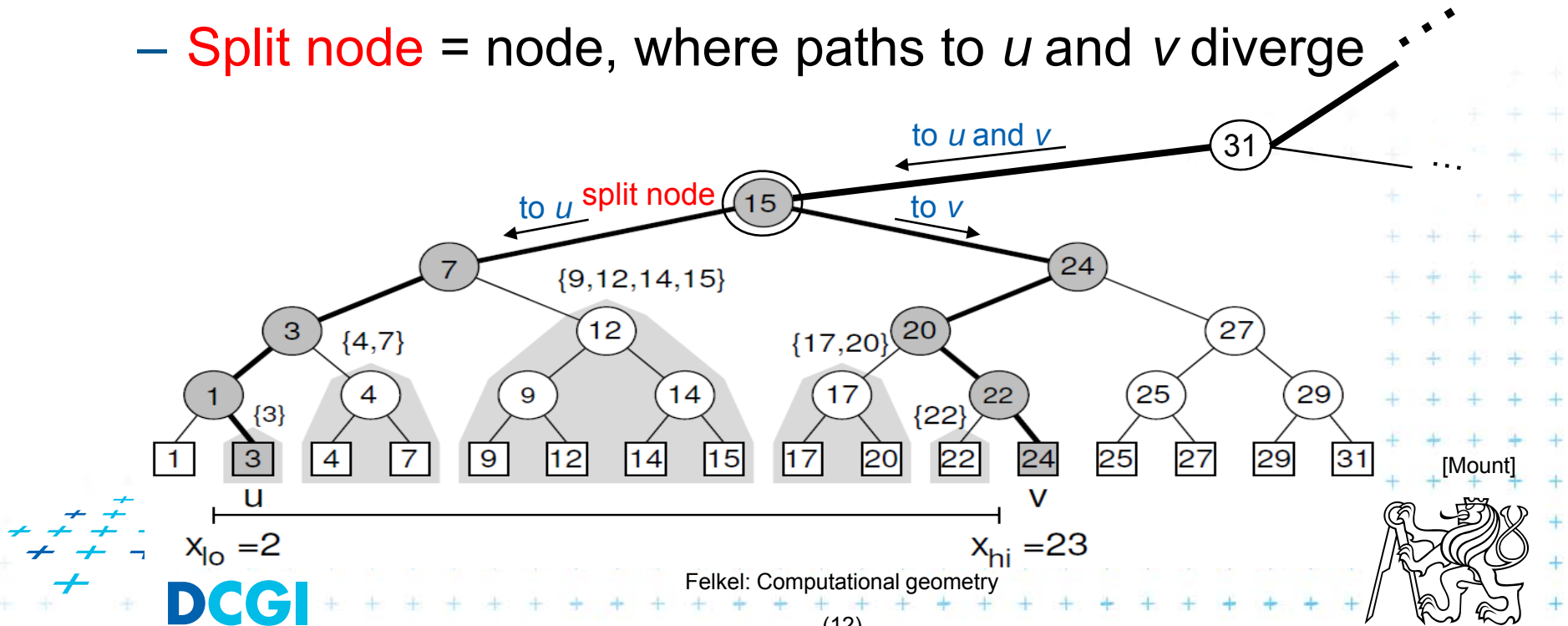
Canonical subsets and $\langle 2,23 \rangle$ search

- Canonical subsets for this subtree are #
 - $\{ \{1\}, \{3\}, \dots, \{31\},$ 16
 - $\{1, 3\}, \{4, 7\}, \dots, \{29, 31\}$ 8
 - $\{1, 3, 4, 7\}, \{9, 12, 14, 15\}, \dots, \{25, 27, 29, 31\}$ 4
 - $\{1, 3, 4, 7, 9, 12, 14, 15\}, \{17, 20, 22, 24, 25, 27, 29, 31\}$ 2
 - $\{1, 3, 4, 7, 9, 12, 14, 15, 17, 20, 22, 24, 25, 27, 29, 31\}$ 1



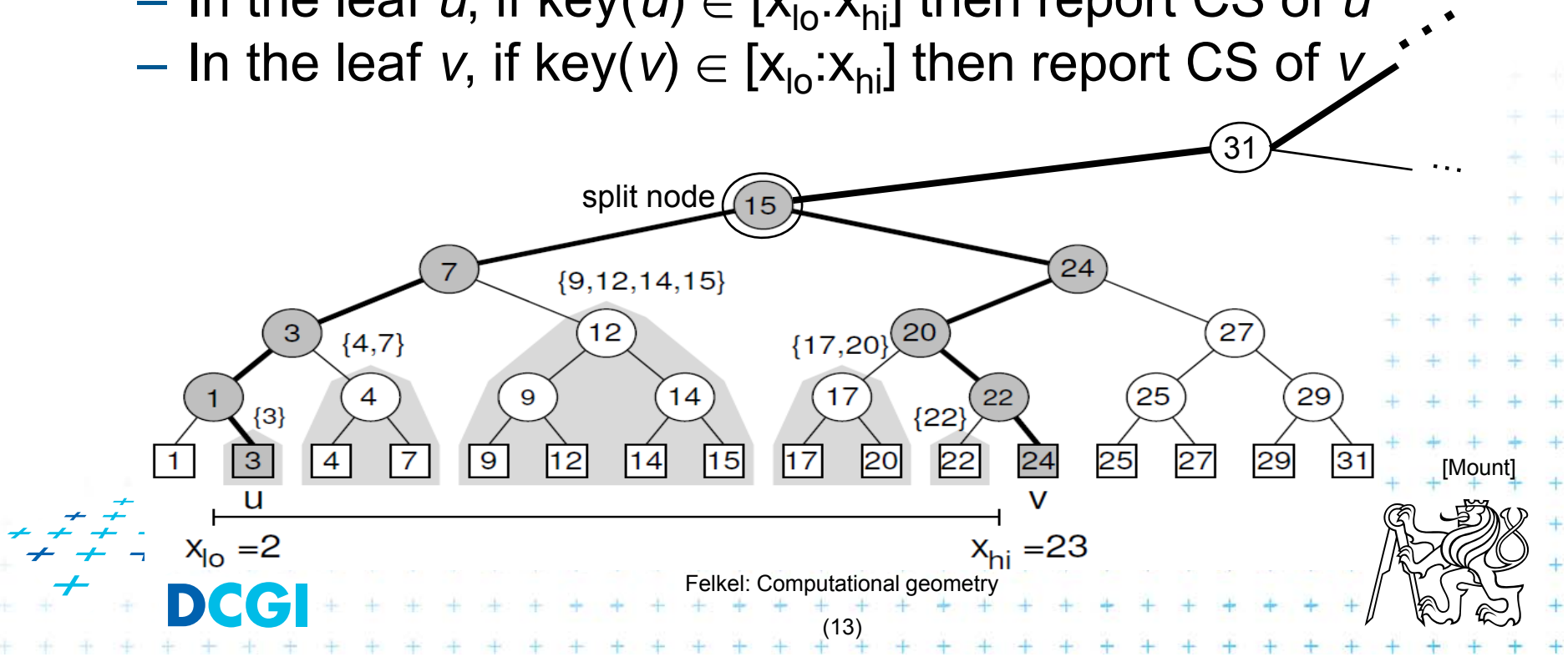
1D range tree search interval $\langle 2, 23 \rangle$

- Canonical subsets for any range found in $O(\log n)$
 - Search x_{lo} : Find leftmost leaf u with $\text{key}(u) \geq x_{lo}$ $2 \rightarrow$ 3
 - Search x_{hi} : Find leftmost leaf v with $\text{key}(v) \geq x_{hi}$ $23 \rightarrow$ 24
 - Points between u and v lie within the range \Rightarrow report canon. subsets of maximal subtrees between u and v
 - **Split node** = node, where paths to u and v diverge



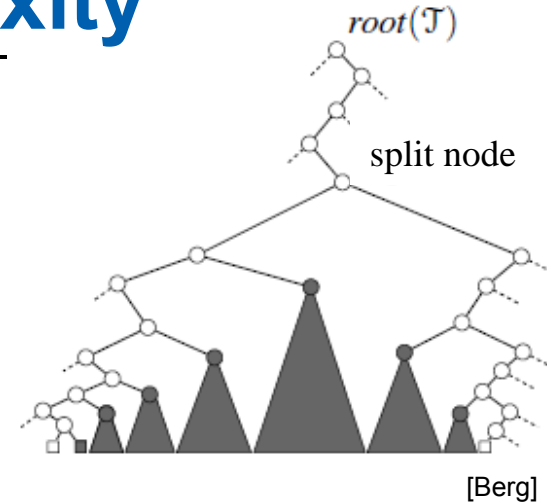
1D range tree search

- Reporting the subtrees (below the split node)
 - On the path to u whenever the *path goes left*, report the canonical subset (CS) associated to right child
 - On the path to v whenever the *path goes right*, report the canonical subset associated to left child
 - In the leaf u , if $\text{key}(u) \in [x_{lo}:x_{hi}]$ then report CS of u
 - In the leaf v , if $\text{key}(v) \in [x_{lo}:x_{hi}]$ then report CS of v

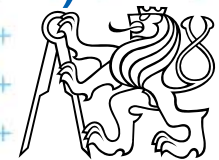


1D range tree search complexity

- Path lengths $O(\log n)$
=> $O(\log n)$ canonical subsets
(subtrees)



- Range counting queries
 - Return just the **number of points in given range**
 - Sum the total numbers of leaves stored in maximal subtree roots ... $O(\log n)$ time
- Range reporting queries
 - Return **all k points in given range**
 - Traverse the canonical subtrees ... $O(\log n + k)$ time
- $O(n)$ storage, $O(n \log n)$ preprocessing (sort P)



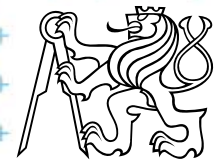
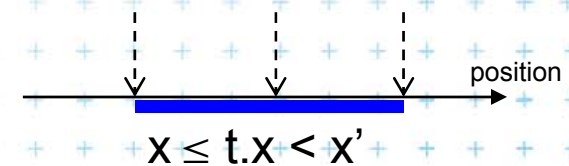
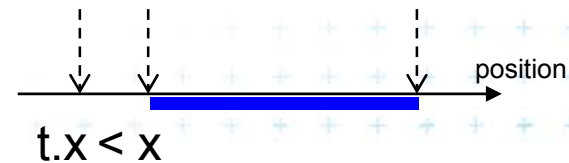
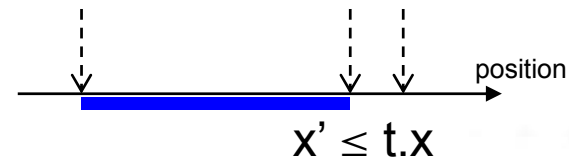
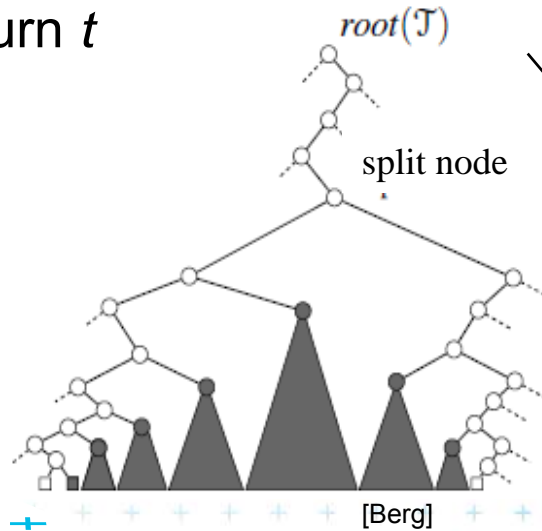
Find split node

FindSplitNode(T , $[x:x']$)

Input: Tree T and Query range $[x:x']$, $x \leq x'$

Output: The node, where the paths to x and x' split or the leaf, where both paths end

1. $t = \text{root}(T)$
2. while(t is not a leaf **and** $(x' \leq t.x$ **or** $t.x < x)$) // out of the range $[x:x']$
3. if($x' \leq t.x$) $t = t.\text{left}$
4. else $t = t.\text{right}$
5. return t



1D range search

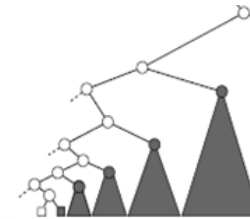
(2D on slide 30)

1dRangeQuery(t , $[x:x']$)

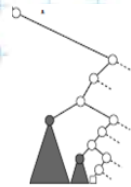
Input: 1d range tree t and Query range $[x:x']$

Output: All points in t lying in the range

1. $t_{\text{split}} = \text{FindSplitNode}(t, x, x')$ // find interval point $t \in [x:x']$
2. if(t_{split} is leaf) // e.g. Searching [16:17] or [16:16.5] both stops in the leaf 17 in the previous example
3. check if the point in t_{split} must be reported // $t_x \in [x:x']$
4. else // follow the path to x , reporting points in subtrees right of the path
5. $t = t_{\text{split}}.\text{left}$
6. while(t is not a leaf)
7. if($x \leq t.x$)
8. **ReportSubtree($t.\text{right}$)** // any kind of tree traversal
9. $t = t.\text{left}$
10. else $t = t.\text{right}$
11. check if the point in leaf t must be reported
12. // Symmetrically follow the path to x' reporting points left of the path



$t = t_{\text{split}}.\text{right} \dots$



Multidimensional range searching

- Equal principle – find the largest subtrees contained within the range
- Separate one n -dimensional search into n 1-dimensional searches
- Different tree organization
 - Kd tree
 - Orthogonal (Multilevel) range search tree
e.g. nd range tree



Kd-tree

- Easy to implement
- Good for different searching problems (counting queries, nearest neighbor,...)
- Designed by Jon Bentley as k-dimensional tree (2-dimensional kd-tree was a 2-d tree, ...)
- Not the asymptotically best for orthogonal range search (=> range tree is better)
- Types of queries
 - Reporting – points in range
 - Counting – number of points in range



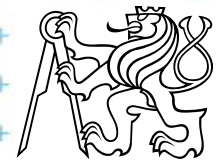
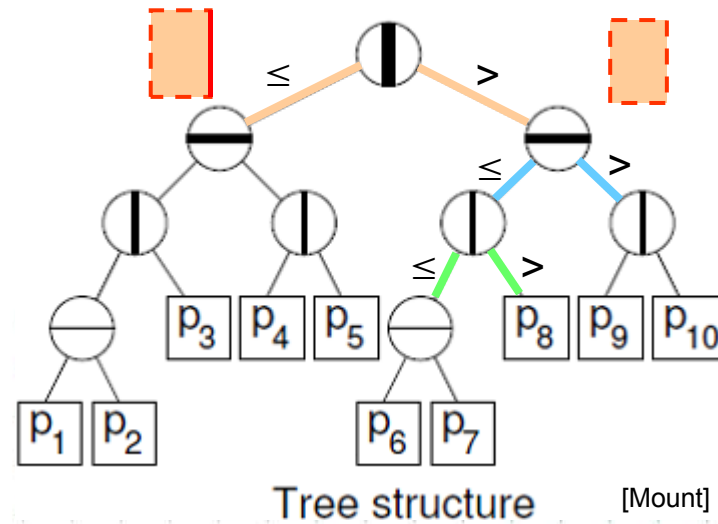
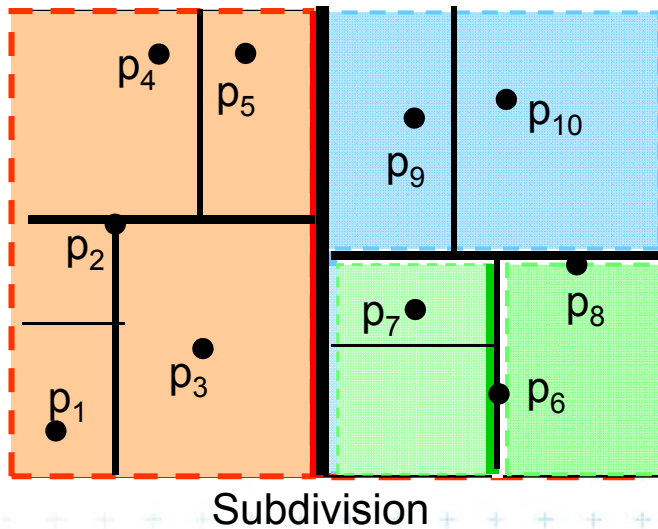
Kd-tree principle

- Which dimension to cut? (cutDim)
 - Cycle through dimensions (round robin)
 - Save storage – cutDim is implicit ~ depth in the tree
 - May produce elongated cells (if uneven data distribution)
 - Greatest spread (the largest difference of coordinates)
 - Adaptive
 - Called “Optimal kd-tree”
- Where to cut? (cutVal)
 - Median, or midpoint between upper and lower median
-> $O(n)$
 - Presort coords of points in each dimension (x-, y-, ...)
for $O(1)$ median – resp. $O(d)$ for all d dimensions



Kd-tree principle

- What about points on the cell boundary?
 - Boundary belongs to the left child
 - Left: $p_{\text{cutDim}} \leq \text{cutVal}$
 - Right: $p_{\text{cutDim}} > \text{cutVal}$



Kd-tree construction in 2-dimensions

BuildKdTree(P , $depth$)

Input: A set of points P and current $depth$.

Output: The root of a kD tree storing P .

1. **If** (P contains only one point) [or small set of (10 to 20) points]
2. **then return** a leaf storing this point
3. **else if** ($depth$ is even) Split according to ($depth \% max_dim$) dimension
4. **then** split P with a vertical line l through median x into two subsets P_1 and P_2 (left and right from median)
5. **else** split P with a horiz. line l through median y into two subsets P_1 and P_2 (below and above the median)
6. $t_{left} = \text{BuildKdTree}(P_1, depth+1)$
7. $t_{right} = \text{BuildKdTree}(P_2, depth+1)$
8. create node t storing l , t_{left} and t_{right} children // $l = \text{cutDim}, \text{cutVal}$
9. **return** t

If median found in $O(1)$ and array split in $O(n)$
 $T(n) = 2 T(n/2) + n \Rightarrow O(n \log n)$ construction

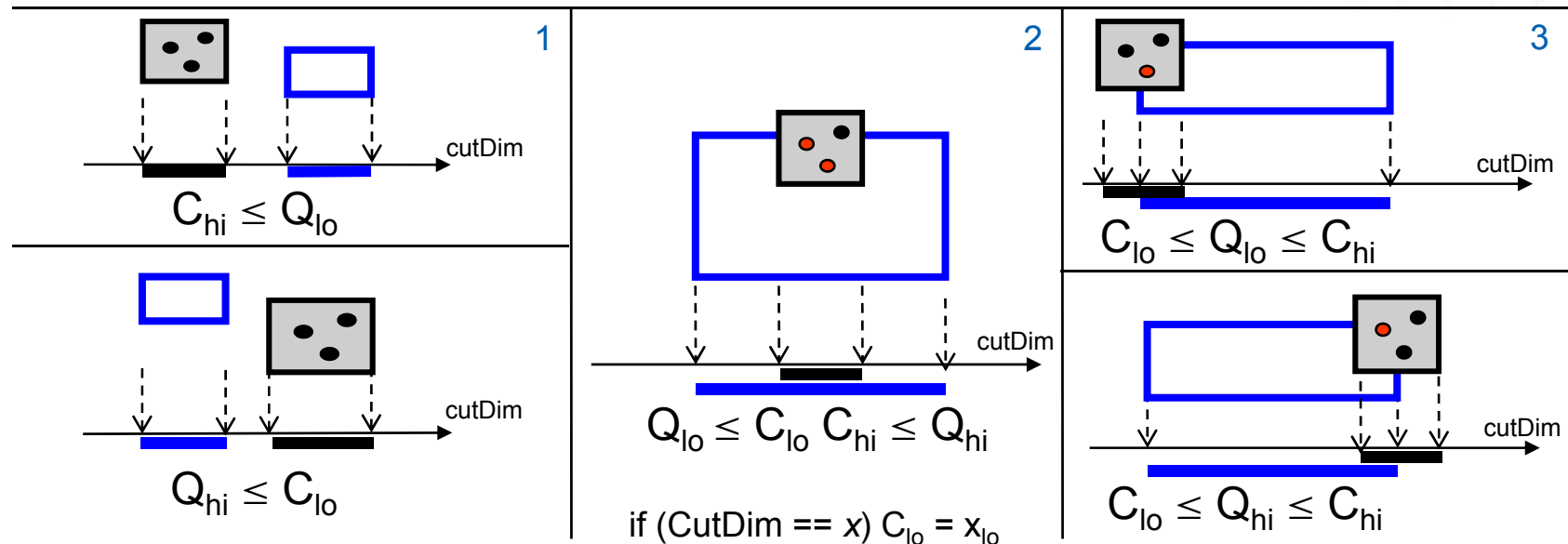


Kd-tree test variants

Test interval-interval

a) Compare rectang. array Q with rectangular cells C

- Rectangle $C:[x_{lo}, x_{hi}, y_{lo}, y_{hi}]$ – computed on the fly
- Test of kD node cell C against query Q (in one cutDim)
 1. if cell is disjoint with Q ... $C \cap Q = \emptyset$... stop
 2. If cell C completely inside Q ... $C \subseteq Q$... stop and report cell points
 3. else cell C overlaps Q ... recurse on both children
- Recursion stops on the largest subtree (in/out)








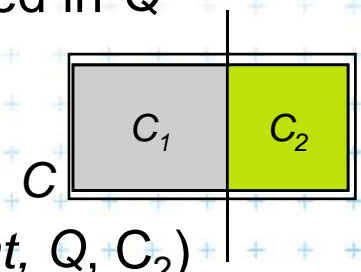
Kd-tree rangeCount (with rectangular cells)

int rangeCount(t , Q , C)

Input: The root t of kd tree, query range Q and t 's cell C .

Output: Number of points at leaves below t that lie in the range.

1. **if** (t is a leaf)
2. **if** ($t.point$ lies in Q) return 1  // or loop this test for all points in leaf
3. **else** return 0  // visited, not counted
4. **else** // (t is not a leaf)
5. **if** ($C \cap Q = \emptyset$) return 0  ... disjoint
6. **else if** ($C \subseteq Q$) return $t.size$  ... C is fully contained in Q
7. **else** 
8. split C along t 's cutting value and dimension, creating two rectangles C_1 and C_2 .
9. **return** rangeCount($t.left$, Q , C_1) + rangeCount($t.right$, Q , C_2)

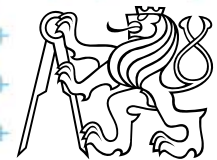
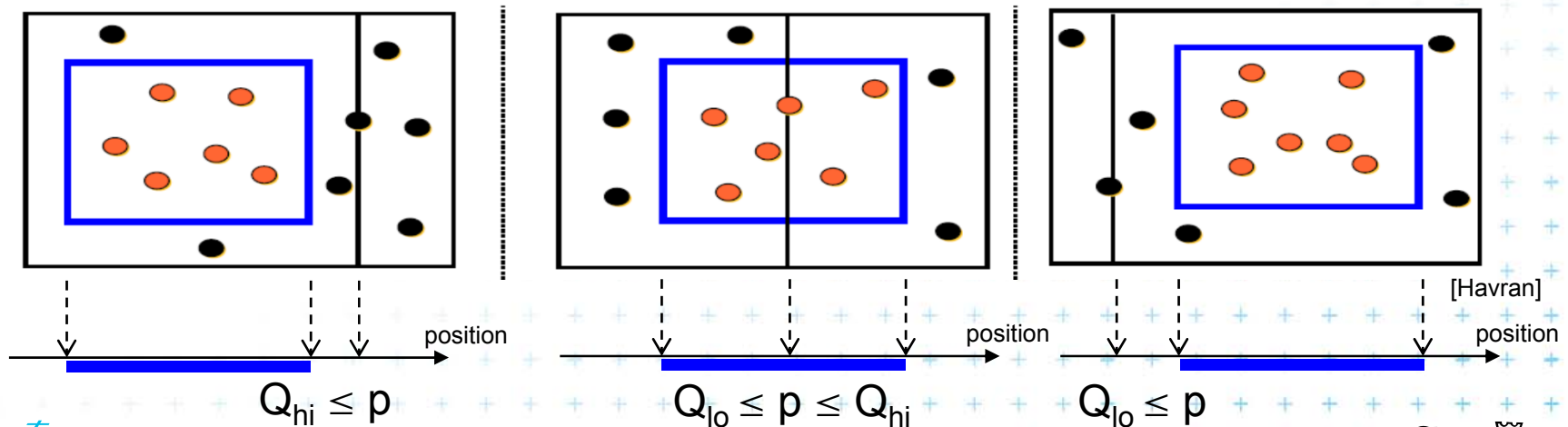


// (pictograms refer to the next slide)



b) Compare Q with cutting lines

- Line = Splitting value p in one of the dimensions
- Test of single position given by dimension against Q
 1. Line p is right from Q ... recurse on left child only (prune right child)
 2. Line p intersects Q ... recurse on both children
 3. Line p is left from Q ... recurse on right child only (prune left ch.)
- Recursion stops in leaves - traverses the whole tree



Kd-tree - summary

- Orthogonal range queries in the plane
(in **balanced** 2d-tree)
 - Counting queries $O(\sqrt{n})$ time
 - Reporting queries $O(\sqrt{n} + k)$ time,
where k = No. of reported points
 - Space $O(n)$
 - Preprocessing: Construction $O(n \log n)$ time
(Proof: if presorted points to arrays in dimensions. Median in $O(1)$
and split in $O(n)$ per level, $\log n$ levels of the tree)
- For $d \geq 2$:
 - Construction $O(d n \log n)$, space $O(dn)$, Search $O(d n^{(1-1/d)} + k)$



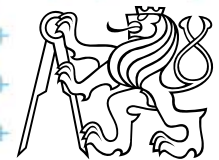
Orthogonal range tree (RT)

- DS highly tuned for orthogonal range queries
- Query times in plane

2d tree	versus	range tree
$O(\sqrt{n} + k)$ time of Kd	>	$O(\log n)$ time query
$O(n)$ space of Kd	<	$O(n \log n)$ space

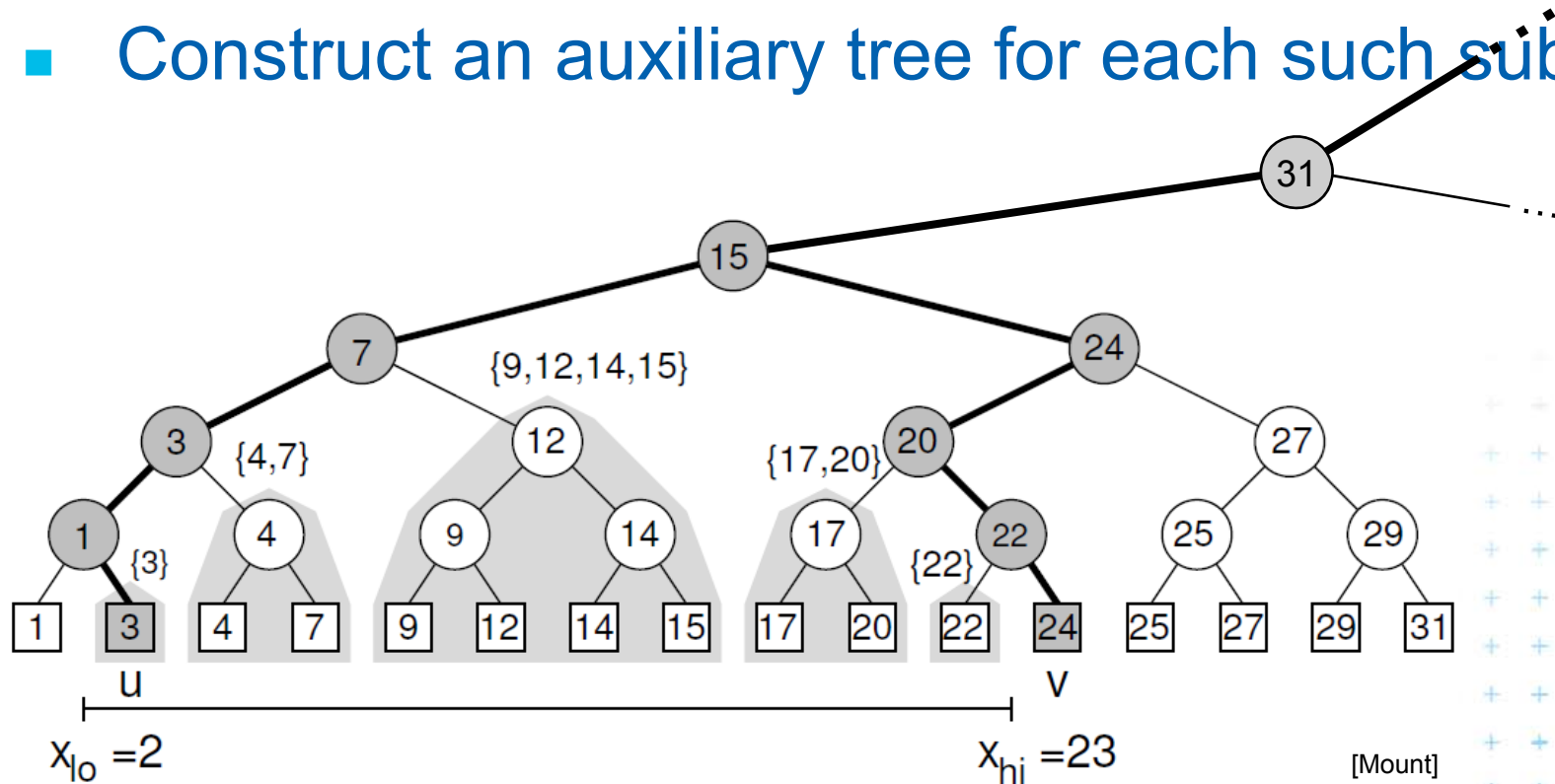
n = number of points

k = number of reported points

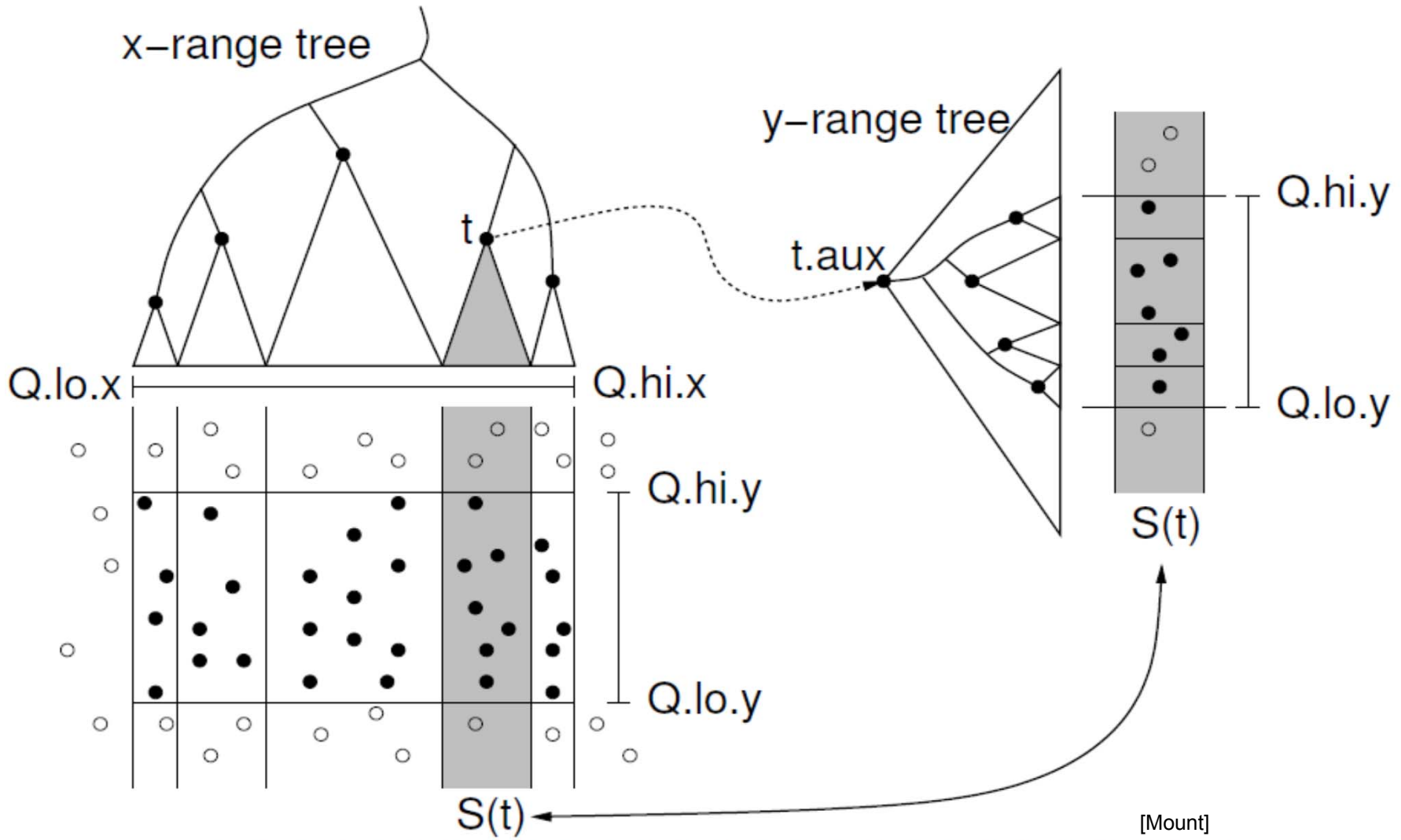


From 1D to 2D range tree

- Search points from $[Q.x_{lo}, Q.x_{hi}] [Q.y_{lo}, Q.y_{hi}]$
- 1d range tree: $\log n$ canonical subsets based on x
- Construct an auxiliary tree for each such subset y



2D range tree



2D range search

2dRangeQuery(t , $[x:x'] \times [y:y']$)

Input: 2d range tree t and Query range

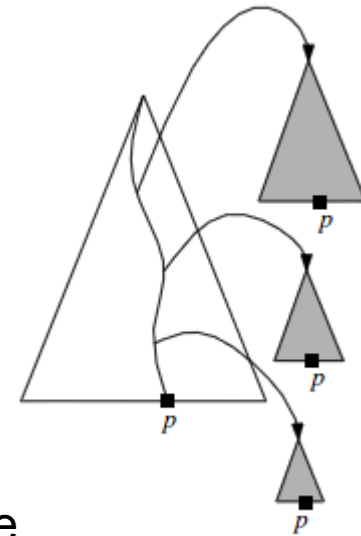
Output: All points in t laying in the range

1. $t_{\text{split}} = \text{FindSplitNode}(t, x, x')$
2. if(t_{split} is leaf)
3. check if the point in t_{split} must be reported ... $t.x \in [x:x']$, $t.y \in [y:y']$
4. else // follow the path to x , calling 1dRangeQuery on y
5. $t = t_{\text{split}}.\text{left}$ // path to the left
6. while(t is not a leaf)
7. if($x \leq t.x$)
8. 1dRangeQuery($t_{\text{assoc}}(t.\text{right}), [y:y']$) // check associated subtree
9. $t = t.\text{left}$
10. else $t = t.\text{right}$
11. check if the point in leaf t must be reported ... $t.x \leq x'$, $t.y \in [y:y']$
12. Similarly for the path to x' ... // path to the right



2D range tree

- Search $O(\log^2 n + k)$ – $\log n$ in x -, $\log n$ in y
- Space $O(n \log n)$
 - $O(n)$ the tree for x -coords
 - $O(n \log n)$ trees for y -coords
 - Point p is stored in all canonical subsets along the path from root to leaf with p ,
 - once for x -tree level (only in one x -range)
 - each canonical subsets is stored in one auxiliary tree
 - $\log n$ levels of x -tree $\Rightarrow O(n \log n)$ space for y -trees



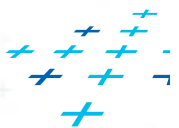
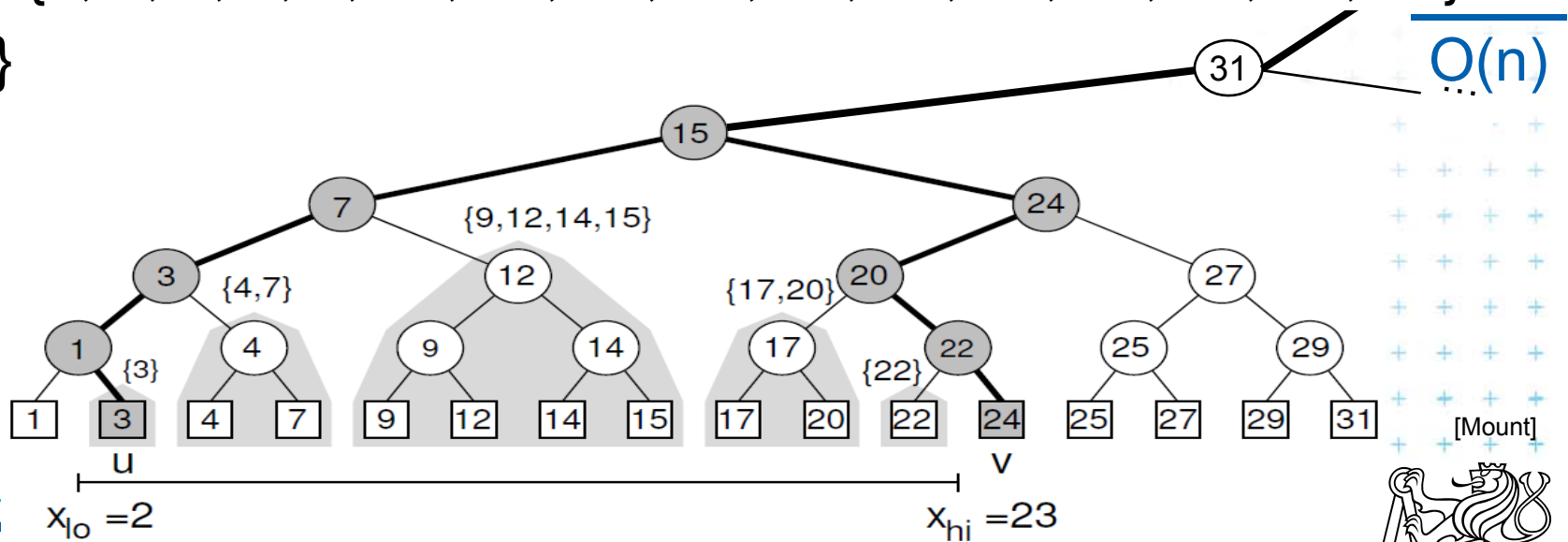
[Berg]

- Construction - $O(n \log n)$
 - Sort points (by x and by y). Bottom up construction

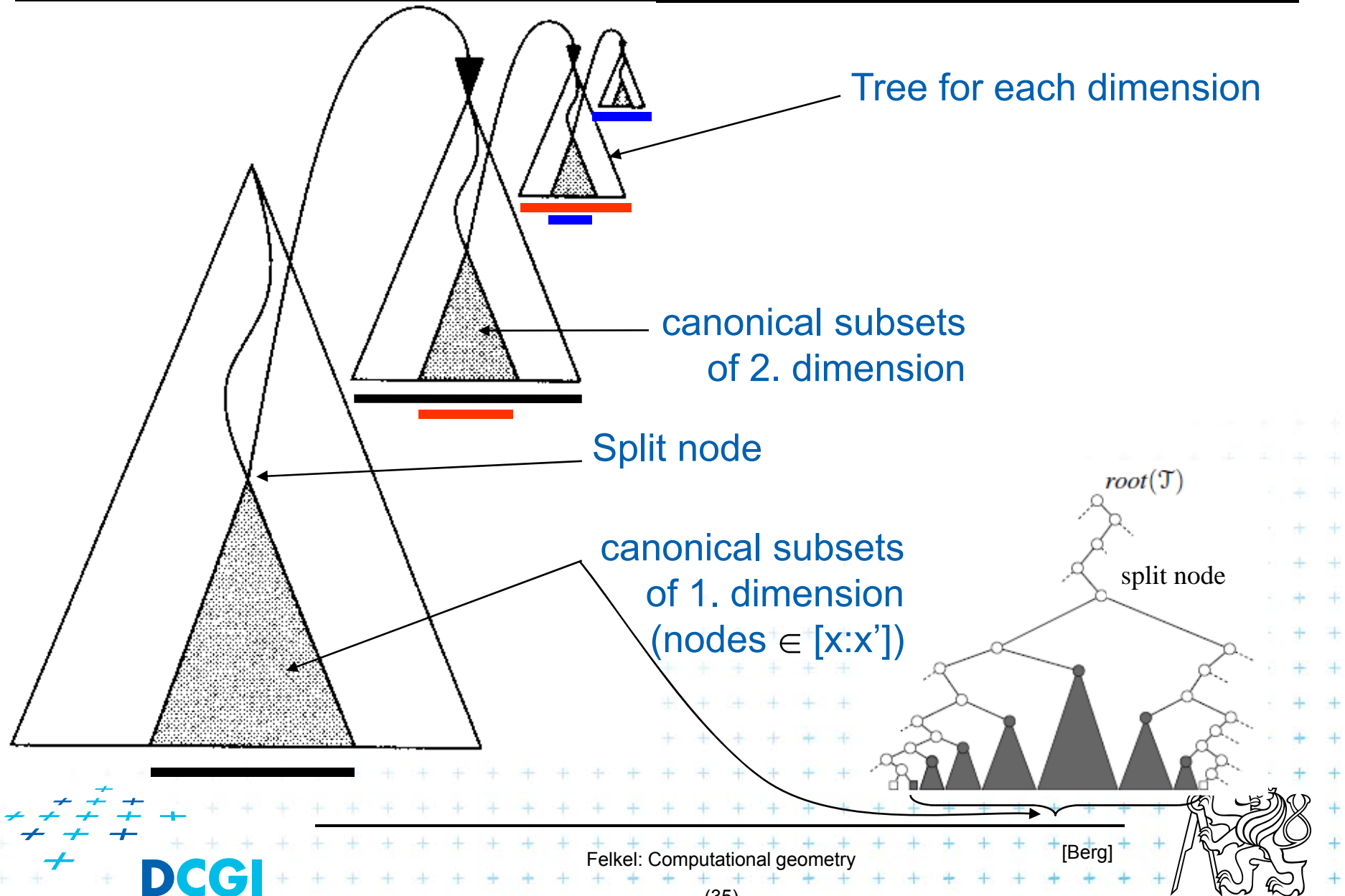


Canonical subsets

- Canonical subsets for this subtree are #
- $\{ \{1\}, \{3\}, \dots, \{31\},$ 16
- $\{1, 3\}, \{4, 7\}, \dots, \{29, 31\}$ 8
- $\{1, 3, 4, 7\}, \{9, 12, 14, 15\}, \dots, \{25, 27, 29, 31\}$ 4
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- $\{1, 3, 4, 7, 9, 12, 14, 15, 17, 20, 22, 24, 25, 27, 29, 31\}$ 1
- $\}$



nD range tree (multilevel search tree)



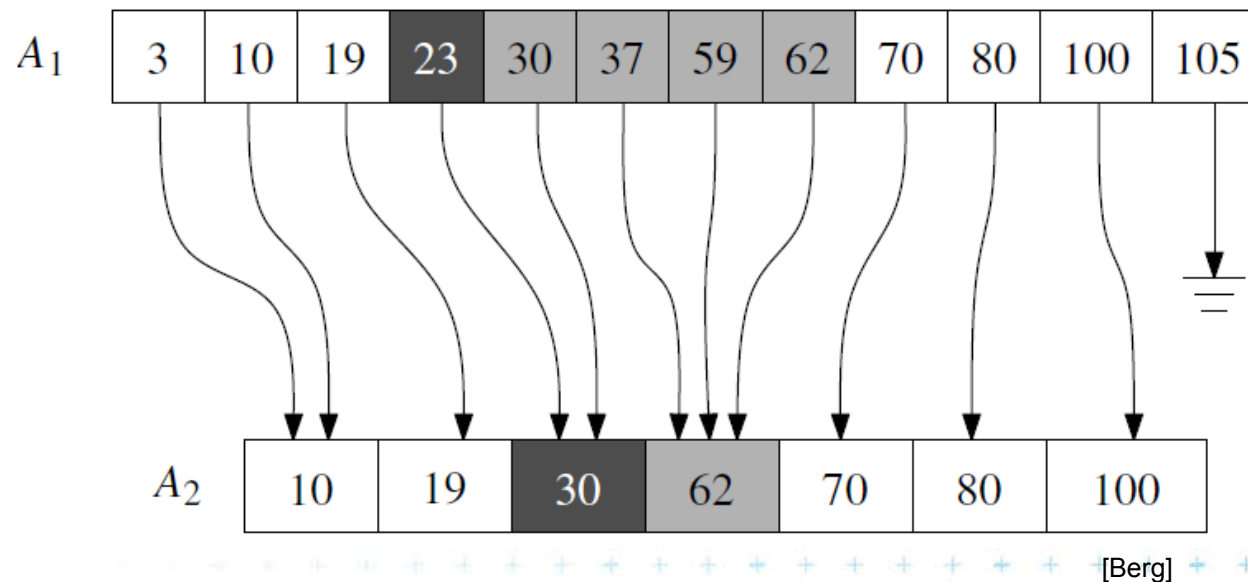
Fractional cascading - principle

- Two sets S_1, S_2 stored in sorted arrays A_1, A_2
- Report objects in both whose keys in $[y:y']$
- Naïve approach
 - $O(\log n_1 + k_1)$ – search in A_1 + report k_1 elements
 - $O(\log n_2 + k_2)$ – search in A_2 + report k_2 elements
- Fractional cascading – adds pointers from A_1 to A_2
 - $O(\log n_1 + k_1 + 1 + k_2)$ – search in A_1 + report k_1 elements
 - $O(1 + k_2)$ – jump to A_2 + report k_2 elements
 - Saves the $O(\log n_2)$ – search



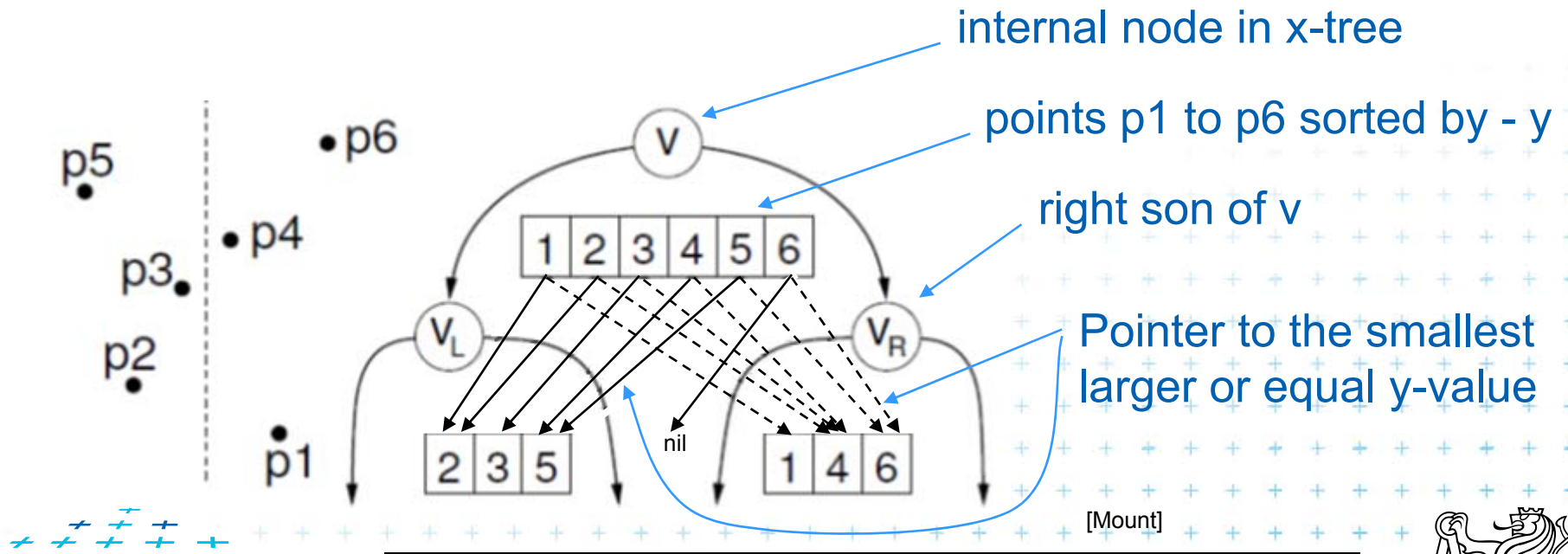
Fractional cascading – principle for arrays

- Add pointers from A_1 to A_2
 - From element in A_1 with a key y_i point to the element in A_2 with the smallest key *larger or equal* to y_i
- Example query with the range [20 : 65]



Fractional cascading in the 2D range tree

- How to save one $\log n$ during last dim. search?
 - Store canonical subsets in arrays sorted by y
 - Pointers to subsets for both child nodes v_L and v_R
 - $O(1)$ search in lower levels \Rightarrow in two dimensional search $O(\log^2 n)$ time $\rightarrow O(2 \log n)$



Orthogonal range tree - summary

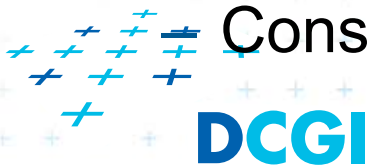
■ Orthogonal range queries in plane

- Counting queries $O(\log^2 n)$ time,
or with fractional cascading $O(\log n)$ time
- Reporting queries plus $O(k)$ time, for k reported points
- Space $O(n \log n)$
- Construction $O(n \log n)$

■ Orthogonal range queries in d -dimensions, $d \geq 2$

- Counting queries $O(\log^d n)$ time,
or with fractional cascading $O(\log^{(d-1)} n)$ time
- Reporting queries plus $O(k)$ time, for k reported points
- Space $O(n \log^{(d-1)} n)$

Construction $O(n \log^{(d-1)} n)$ time



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