CS 240 – Data Structures and Data Management

Module 8: Range-Searching in Dictionaries for Points

O. Veksler

Based on lecture notes by many previous cs240 instructors

David R. Cheriton School of Computer Science, University of Waterloo

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Outline

- Range-Searching in Dictionaries for Points
  - Range Search
  - Multi-Dimensional Data
  - Quadtrees
  - kd-Trees
  - Range Trees
  - Conclusion

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Range Searches

- *search*(k) looks for *one* specific item
- New operation *RangeSearch* (x, x')
  - look for *all* items that fall within given range (interval) $Q = (x, x')$
    - Q may have open or closed ends
  - report all KVPs in the dictionary with $k \in Q$
  - example

$s = 3, n = 10$

5	**10**	**11**	**17**	**18**	**33**	**45**	**51**	**55**	**77**

RangeSearch $(17,45]$ should return $\{18, 33, 45\}$

- As usual, n is the number of input items
- Let s be the output-size, i.e. the number of items in the range
- Need $\Omega(s)$ time just to report the items in the range
  - s can be anything between 0 and n (it depends on input interval Q)
- Therefore, running time depends **both** on s and n
  - so keep s as a parameter when analyzing runtime
  - getting $O(n)$ time is trivial
    - can we get $O(\log n + s)$?

Range Search in Existing Dictionary Realizations

- *Unsorted list/array/hash table*
  - range search requires $\Omega(n)$ time
    - must check for each item explicitly if it is in the range
- *Sorted array*

5	**10**	**11**	**17**	**18**	**33**	**45**	**51**	**55**	**77**
			i				i'		

  - *RangeSearch* $(16{,}50)$
  - $O(\log n)$ use binary search to find i s.t. x is at (or would be at) $A[i]$
  - $O(\log n)$ use binary search to find i' s.t. x' is at (or would be at) $A[i']$
  - $O(s)$ report all items in $A[i+1 \dots i'-1]$
  - $O(1)$ report $A[i]$ and $A[i']$ if they are in the range
  - range search can be done in $O(\log n + s)$ time
- *BST*
  - can do range search in $O(height + s)$ time
    - details later

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  - Range Search Query
  - Multi-Dimensional Data
  - Quadtrees
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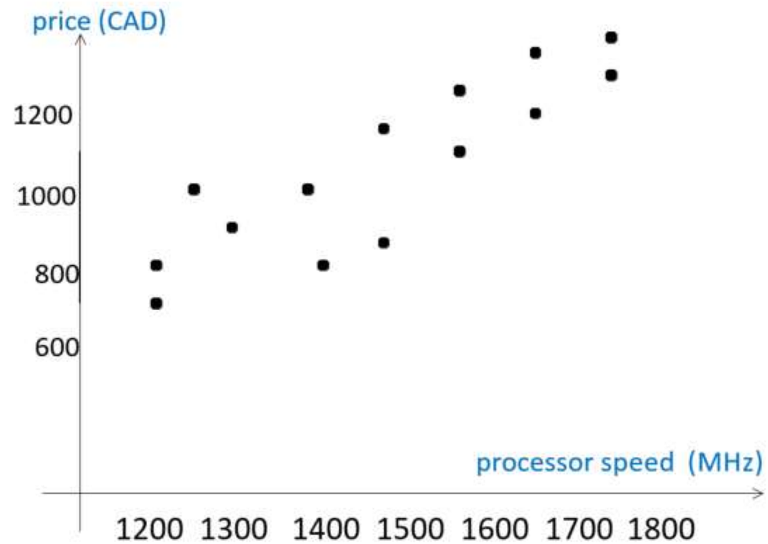
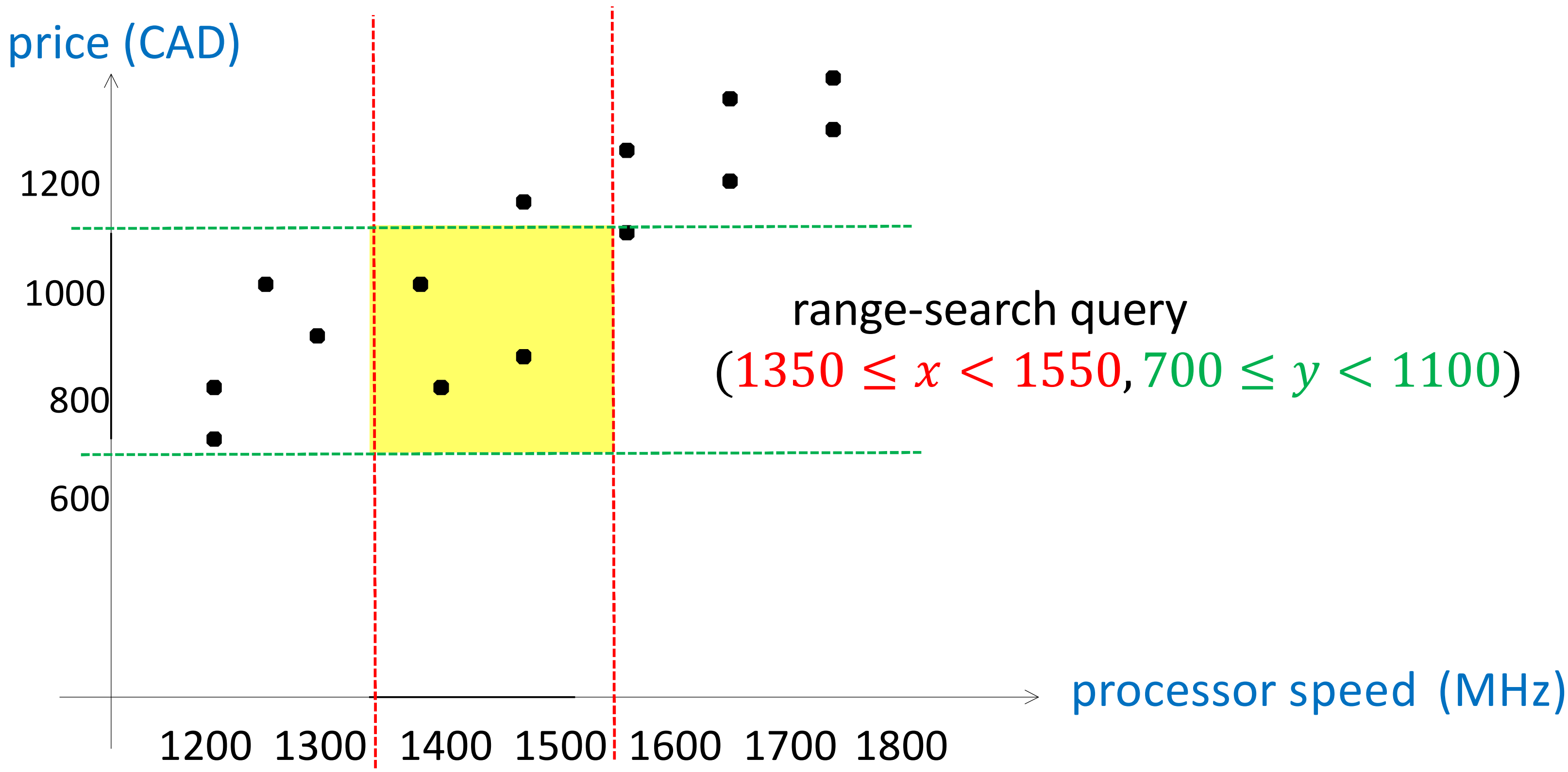
Multi-dimensional Data



- Data with multiple aspects of interest
  - laptops: price, screen size, processor speed, ...
  - employees: name, age, salary, ...
- Range searches are of special interest for multidimensional data
  - flights that leave between 9am and noon, and cost between $400 and $600
- Dictionary for multi-dimensional data
  - collection of d-dimensional items (or points)
  - each item has d aspects (coordinates): $(x_0, x_1, \cdots, x_{d-1})$
  - need usual dictionary operations: *insert*, *delete*, *search*
  - also need *RangeSearch*
- We focus on $d = 2$, i.e. points in Euclidean plane

Multi-Dimensional Range Search

- (Orthogonal) d-dimensional range search
  - given a *query rectangle* Q, find all points that lie within Q

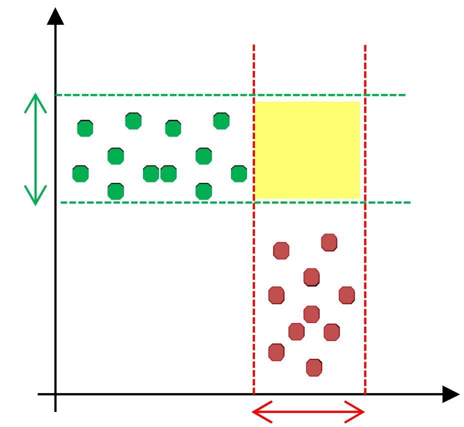


d-Dimensional Dictionary via 1-Dimensional Dictionary

- Option 1: Reduce to one-dimensional dictionary
  - combine d-dimensional key into one dimensional key
    - i.e. $(x, y) \rightarrow x + y \cdot n^2$
    - $(price, screenSize) \rightarrow price + screenSize \cdot n^2$
    - two distinct (x, y) map to a distinct one dimensional key
  - can search for a specific key (x, y)
  - but no efficient range search

d-Dimensional Dictionary via 1-Dimensional Dictionary

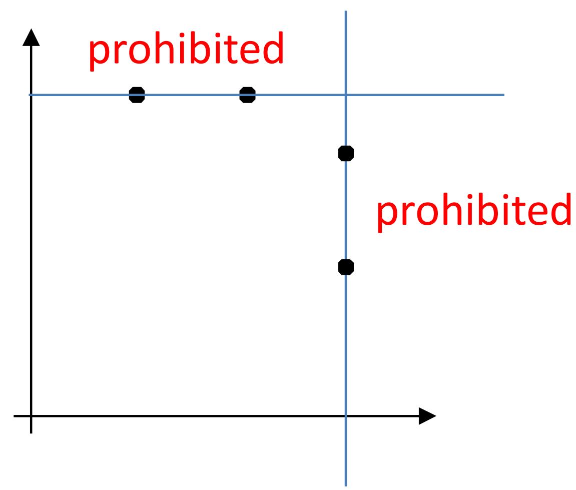
- Option2: Use several dictionaries, one for each dimension
  - problem: wastes space, inefficient search
  - Worst-case example
    - insert all n points in horizontal dictionary
      - key is x coordinate
    - insert all n points in vertical dictionary
      - key is y coordinate



    - 1D range search in horizontal dictionary returns $n/2$ points
    - 1Drange search in vertical dictionary returns $n/2$ points
    - For 2D range search result, need to find points which are both in the red and the green clouds
      - insert $n/2$ red points in AVL tree
      - for each of $n/2$ green point, check if it is in the AVL Tree
    - total time to find points in both clouds is $O(n \log n)$
      - worse than exhaustive search!
      - far from $O(s + \log n)$, especially since $s = 0$

Multi-Dimensional Range Search

- Better idea
  - design new data structures specifically for points
- Assumption: points are in *general position*: no two x-coordinates or y-coordinates are the same
  - i.e. no two points on a horizontal lines, no two points on a vertical line



  - simplifies presentation, data structures can be generalized to arbitrary points

Multi-Dimensional Range Search

- Partition trees
  - organize space to facilitate efficient multidimensional search
    - internal nodes are associated with spatial regions
    - actual dictionary points stored only at leaves
  - We study 2 types of partition trees
    1. quadtrees
       - does not use general points position assumption
    2. kd-trees
       - uses general points position assumption
- Multi-dimensional range trees
  - a tree that generalizes BST to support multidimensional search
  - both internal and leaf nodes store points, similar to one dimensional BST
  - uses general points position assumption

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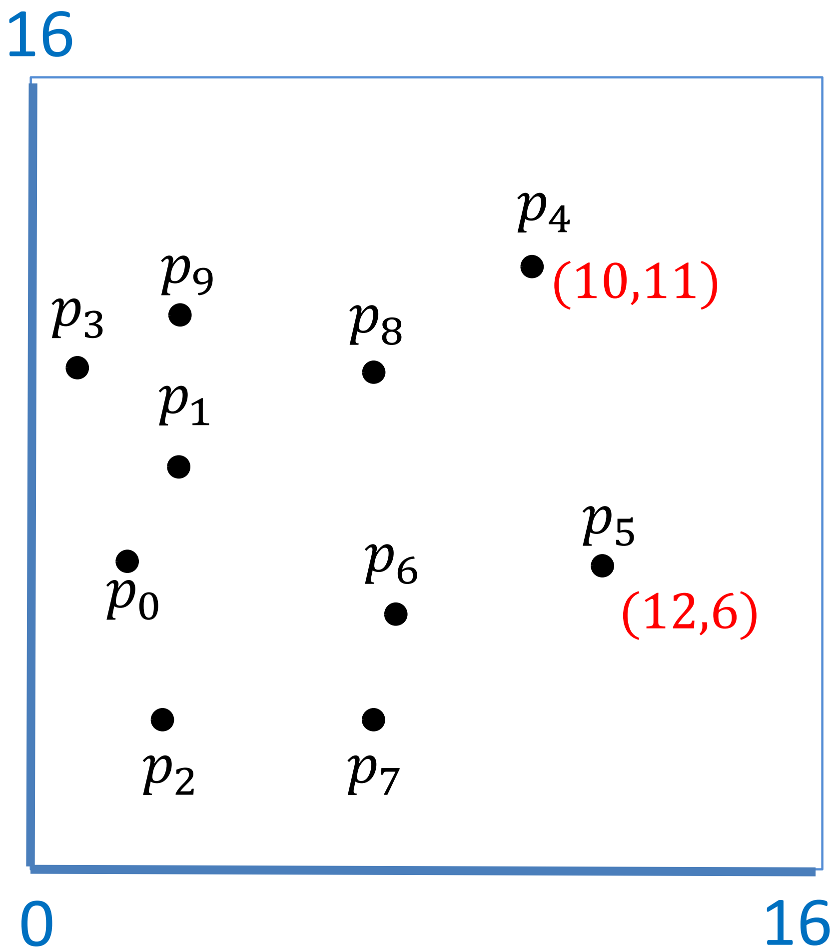
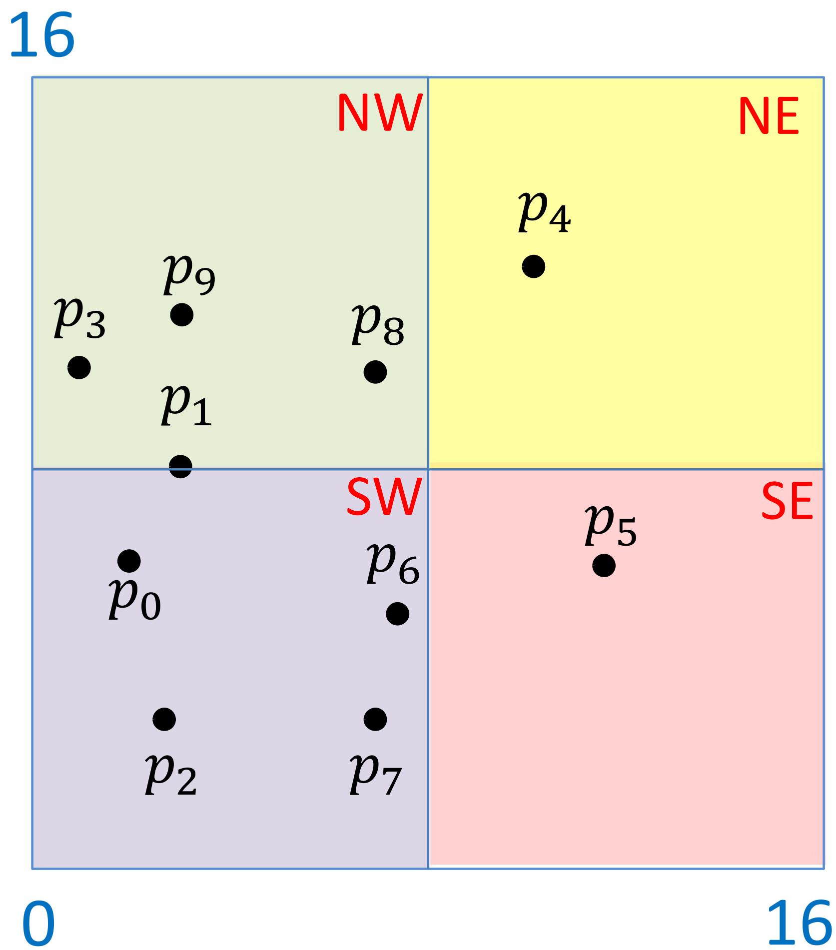
Quadtrees

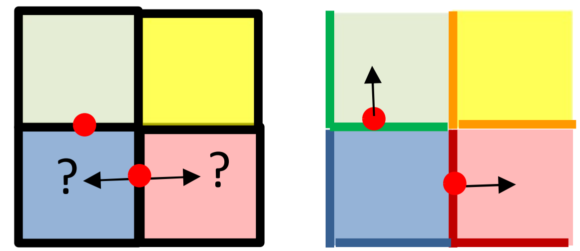


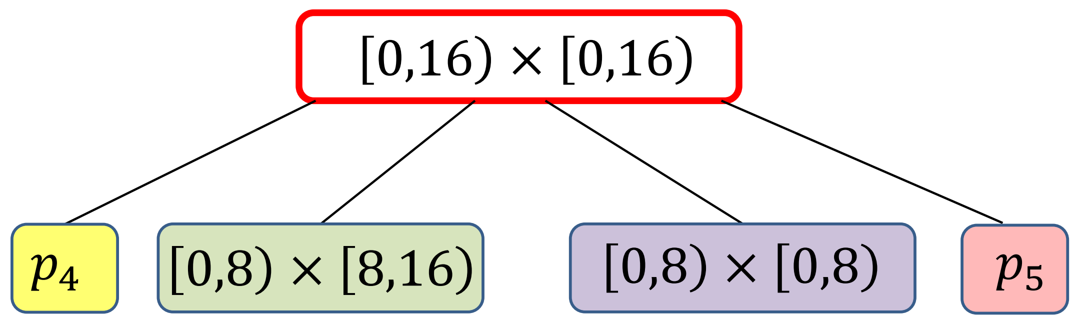
- Have a set S of n points in the plane
- Find *bounding box* $R = [0, 2^k) \times [0, 2^k)$
  - translate points so coordinates are non-negative
  - smallest $2^k \times 2^k$ square containing all points
    - find smallest k s.t. max-coordinate in S is less than 2^k
- Quadtree is a tree
- Each node corresponds to a region
- Higher levels responsible for larger regions
- Leaves responsible for regions small enough to store one point

Quadtree Construction Example



- Root corresponds to the whole square
- Split the square into 4 equal regions
- Convention: points on split lines belong to region on the right (or top)





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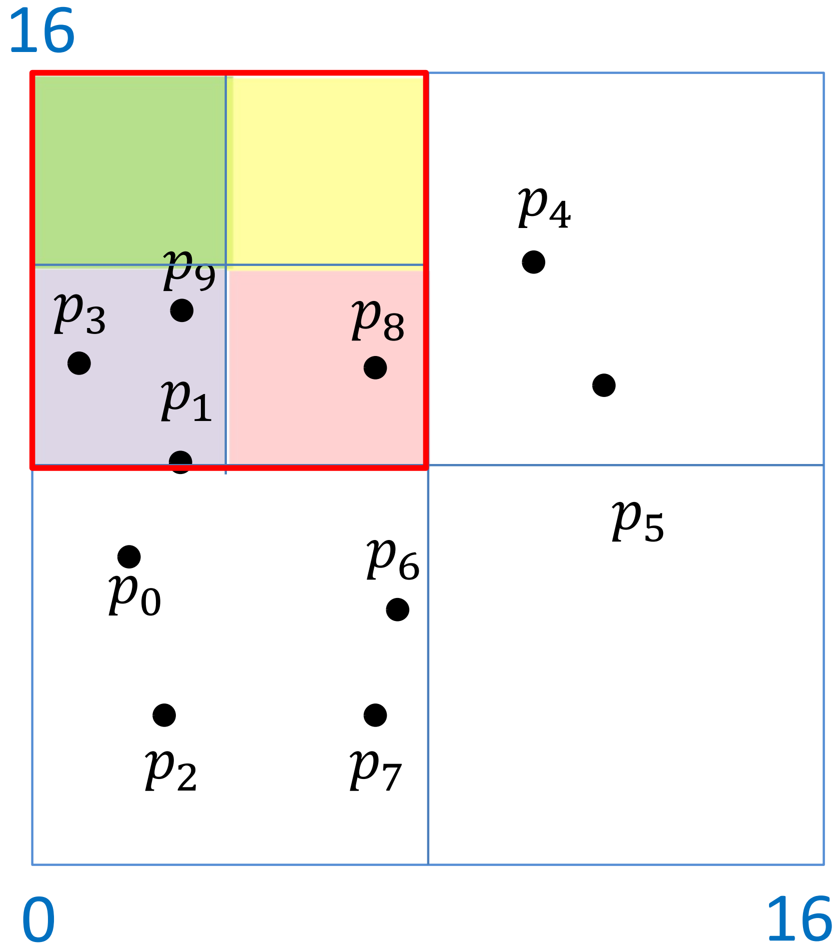
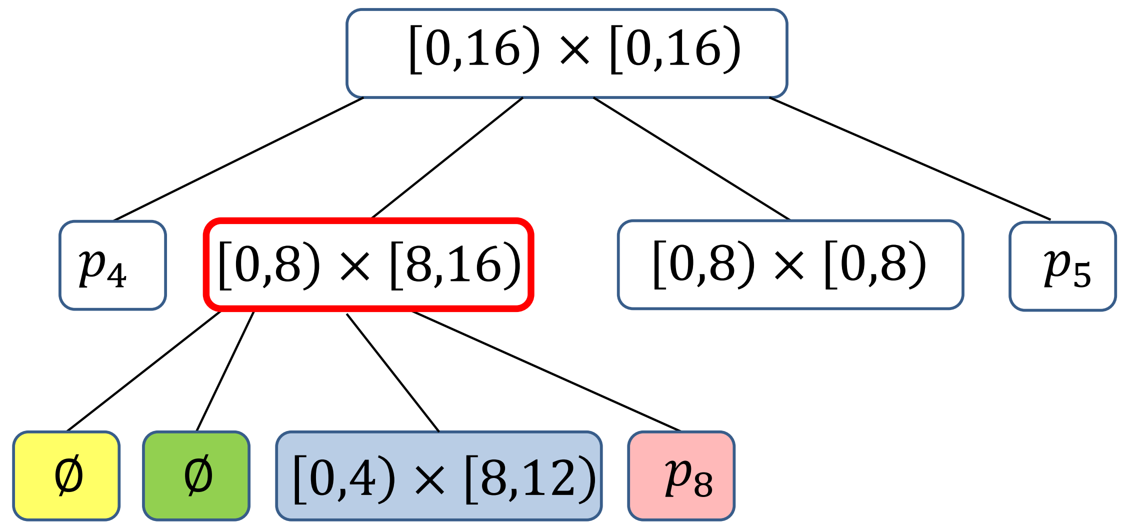
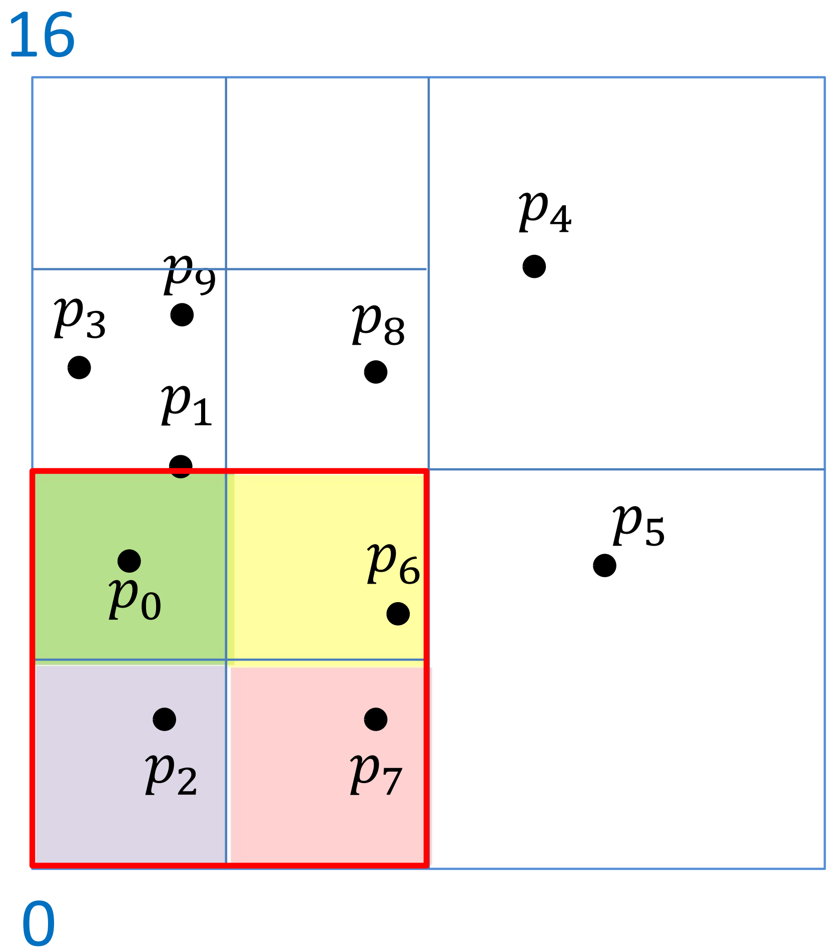


- keep subdividing regions (recursively) into smaller region until each region has at most one point



leaf storing empty-set of points or *empty* leaf

Quadtree Construction Example



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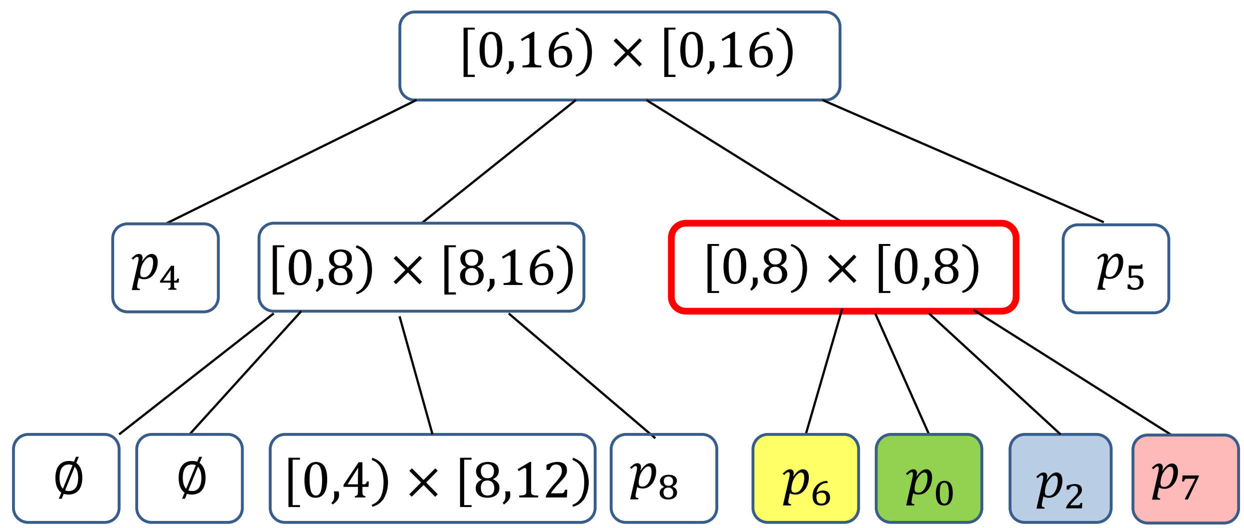
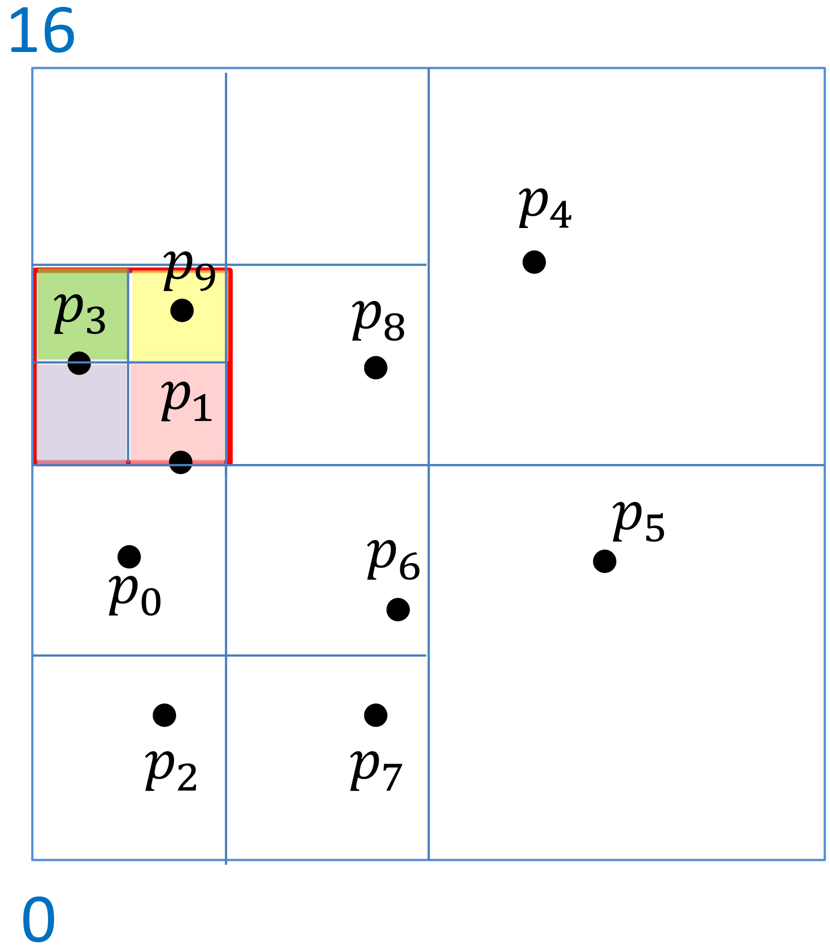


Quadtree Construction Example



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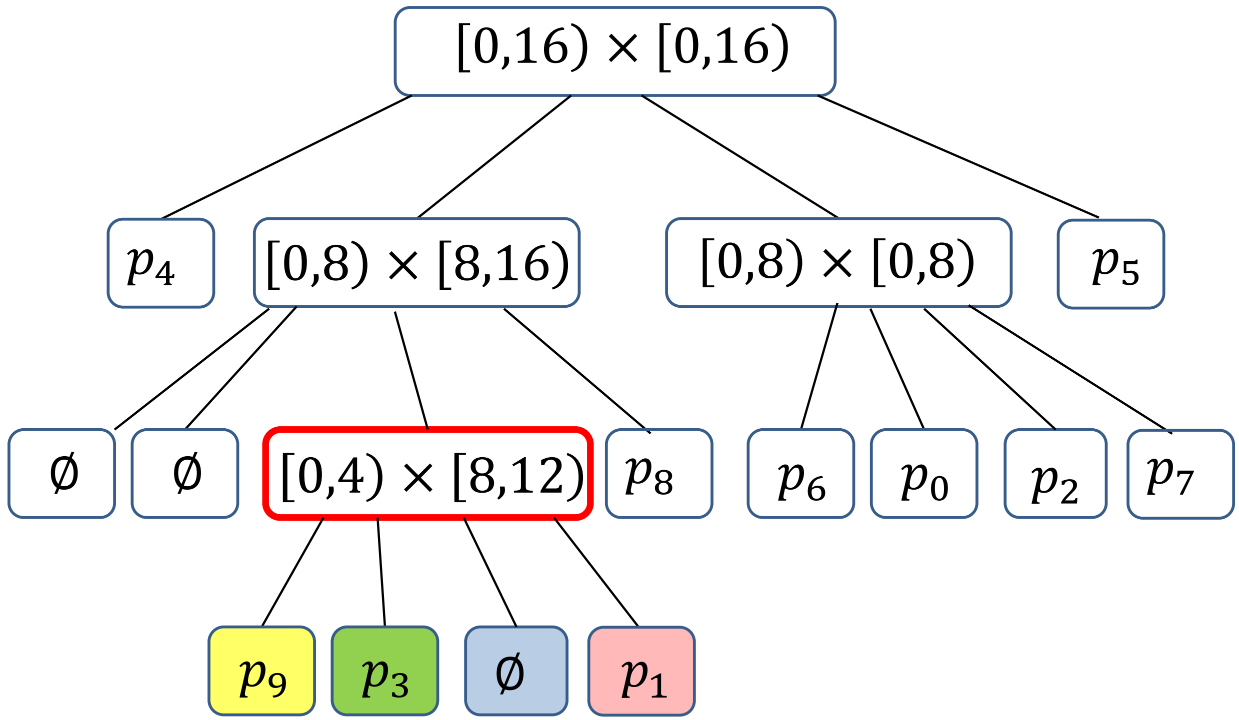


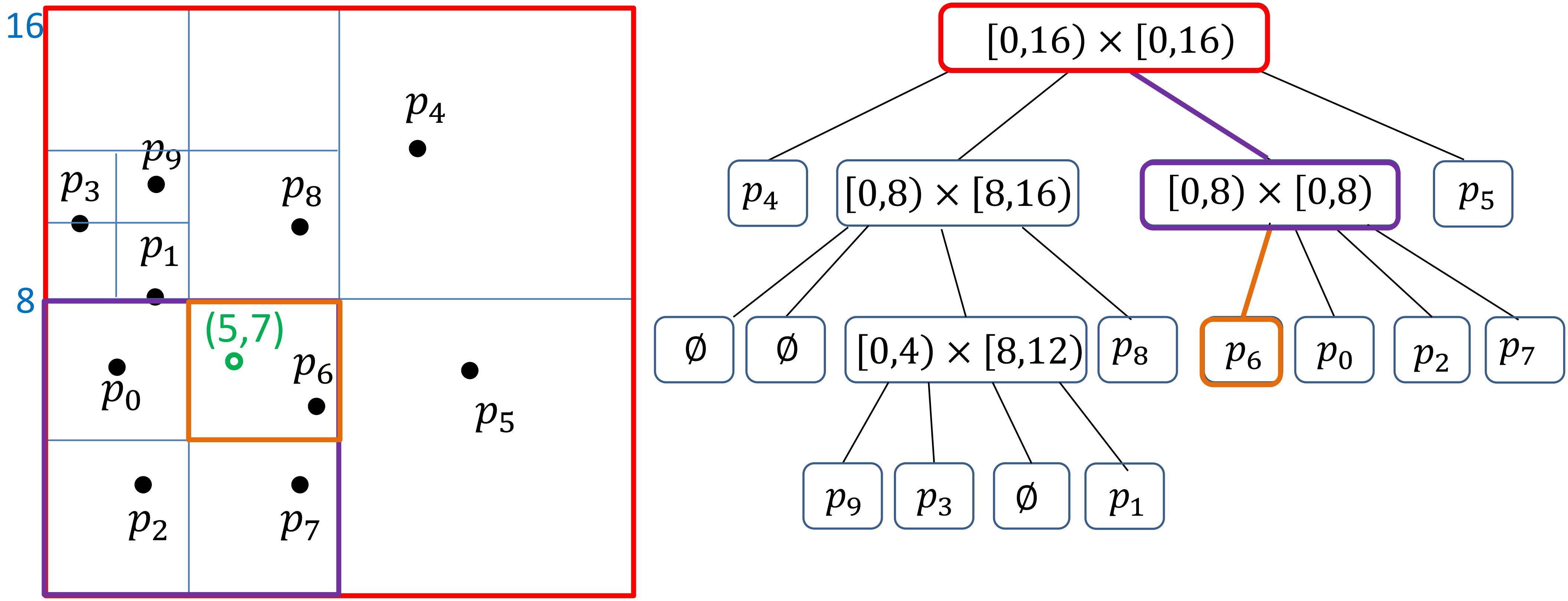
Quadtree Building Summary

- Have n points $S = \{(x_0, y_0), (x_1, y_1), \dots, (x_{n-1}, y_{n-1})\}$
  - all points are within a square R
- To build quadtree on S
  - root r corresponds to R
  - if R contains 0 (or 1) point
    - then root r is an empty leaf (or a leaf that stores 1 point)
  - else
    - partition R into four equal subsquares (quadrants) $R_{NE}, R_{NW}, R_{SW}, R_{SE}$
    - partition S into sets $S_{NE}, S_{NW}, S_{SW}, S_{SE}$
      - convention: points on split lines belong to region on the right (or top)
    - recursively build tree T_i for points S_i in R_i and make them children of root

Quadtree Search

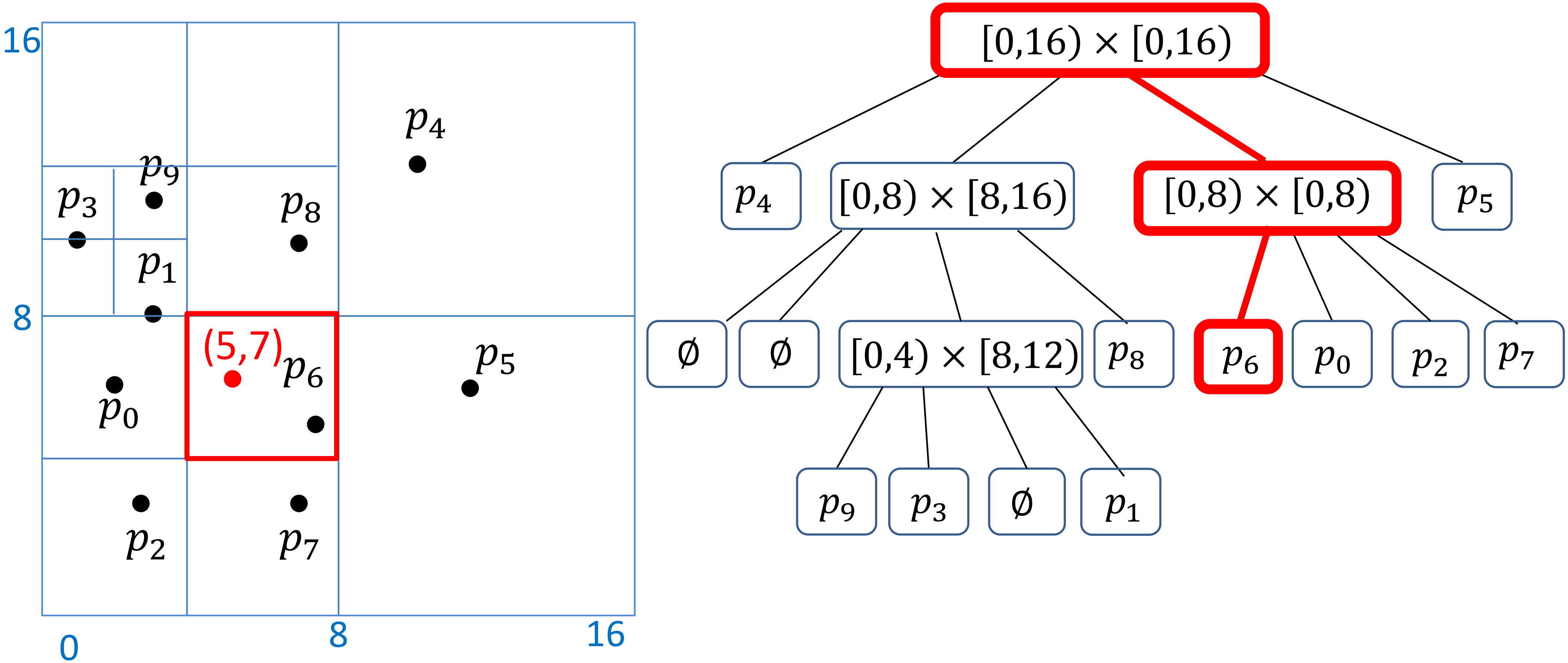
- Whenever possible, search rules out regions at higher level of hierarchy, achieving efficiency

Quadtree Search



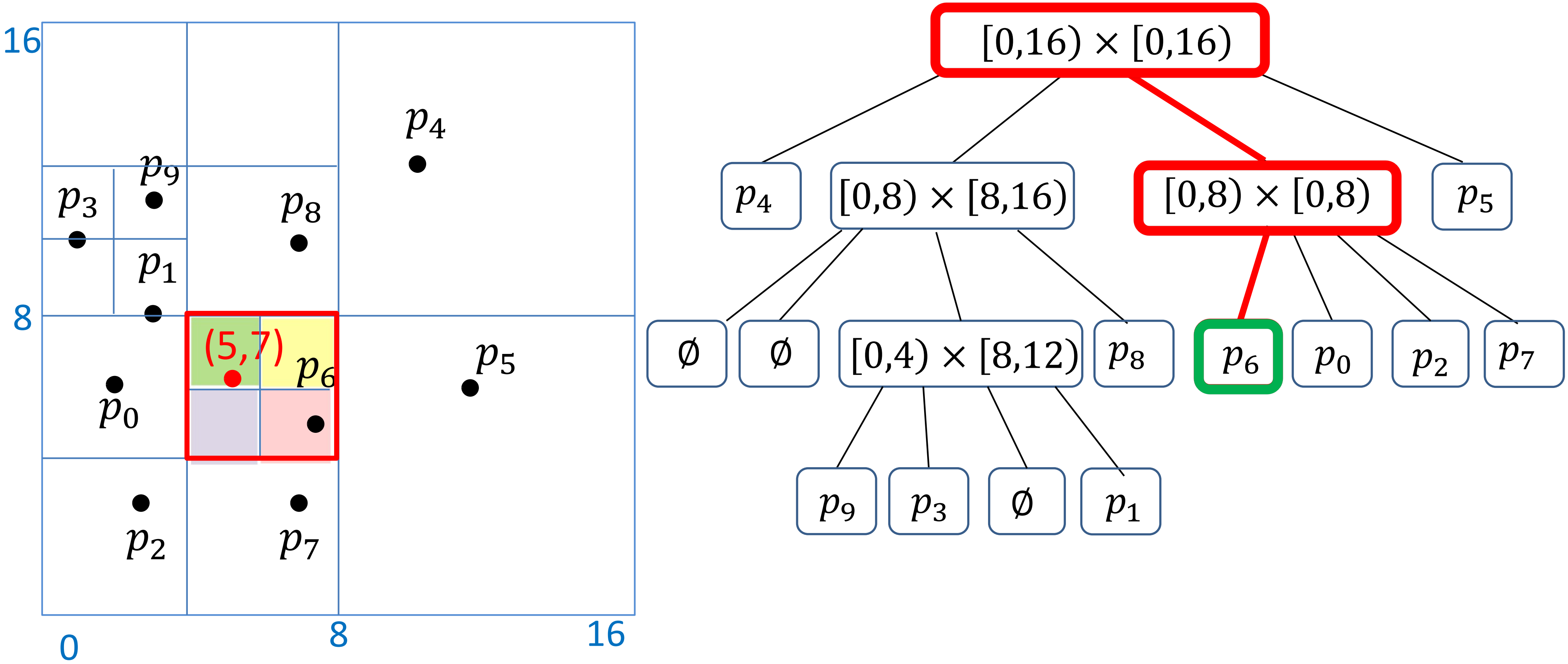
- Analogous to trie or BST
- Three possibilities for where search ends
    1. leaf storing point we search for (found)
    2. leaf storing point different from search point (not found)
    3. empty leaf (not found)
- Example: search(5,7) (not found)
- Search is efficient if quadtree has small height

Quadtree Insert



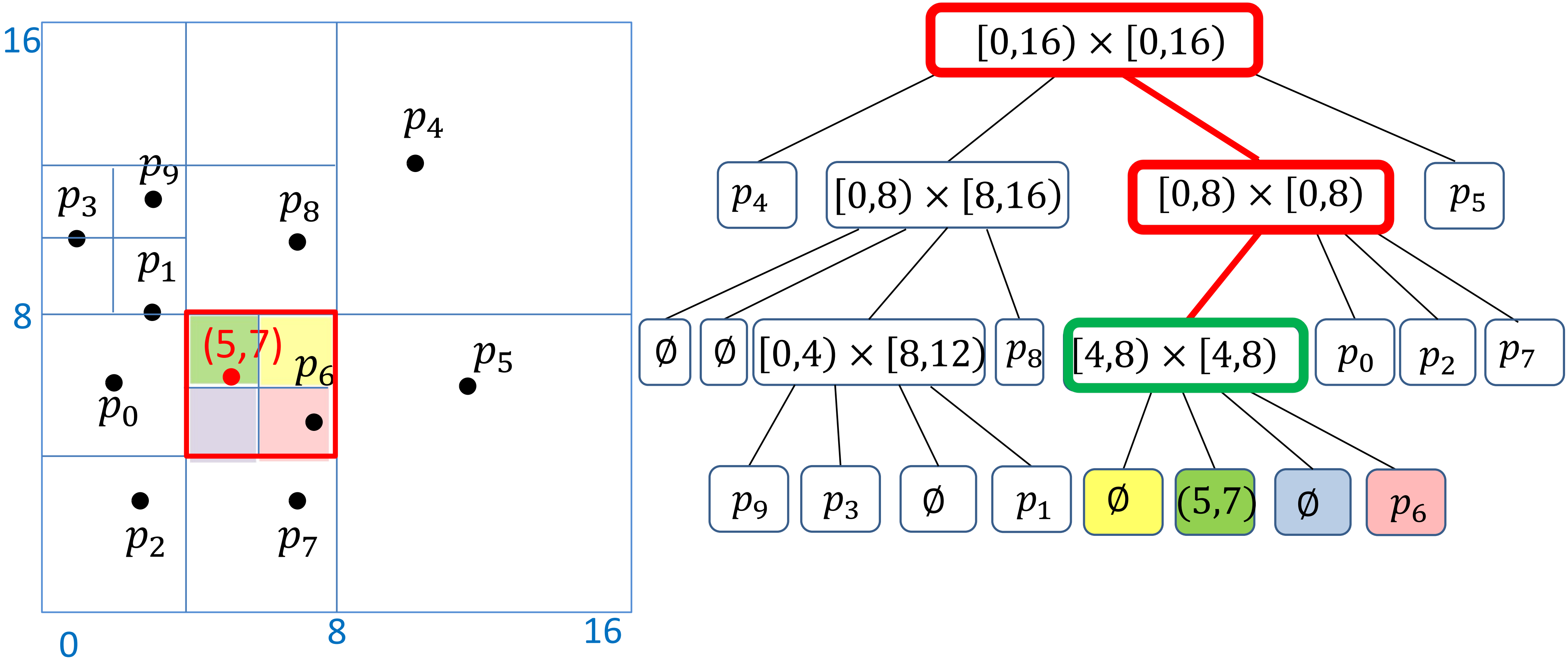
- First perform search
- Two cases
    1. search finds a leaf storing one point
        - example: insert(5,7)

Quadtree Insert



- First perform search
- Two cases
  1. search finds a leaf storing one point
     - example: insert(5,7)
     - repeatedly split the leaf **while** there are two points in one region

Quadtree Insert



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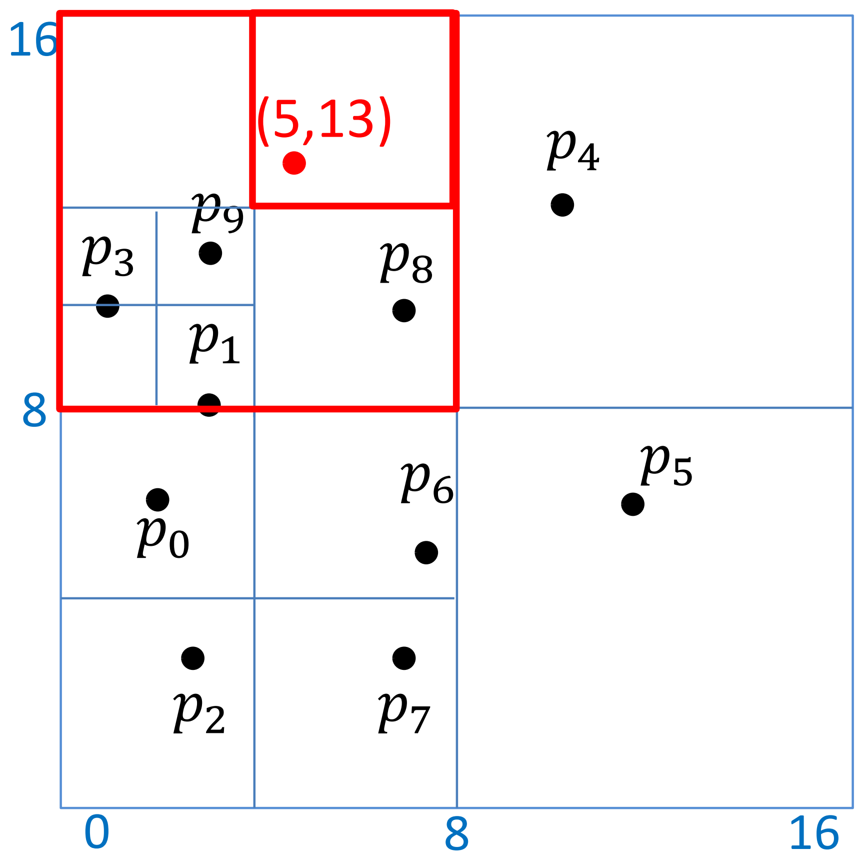
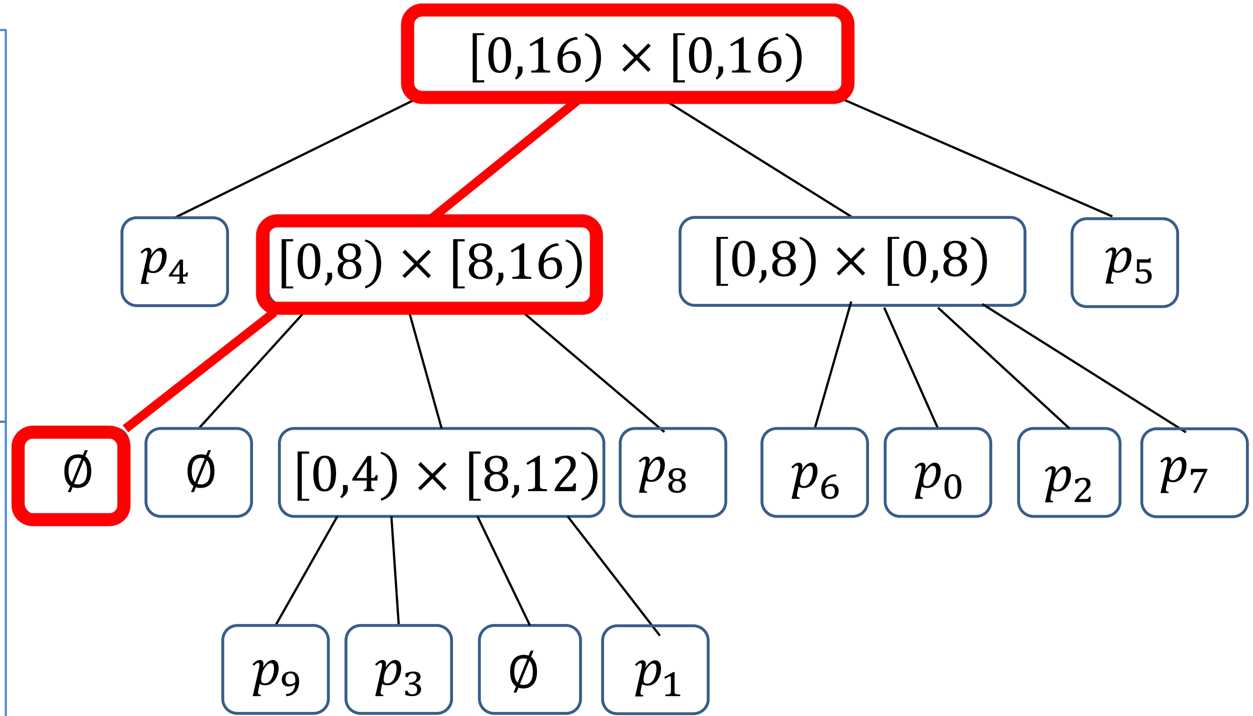
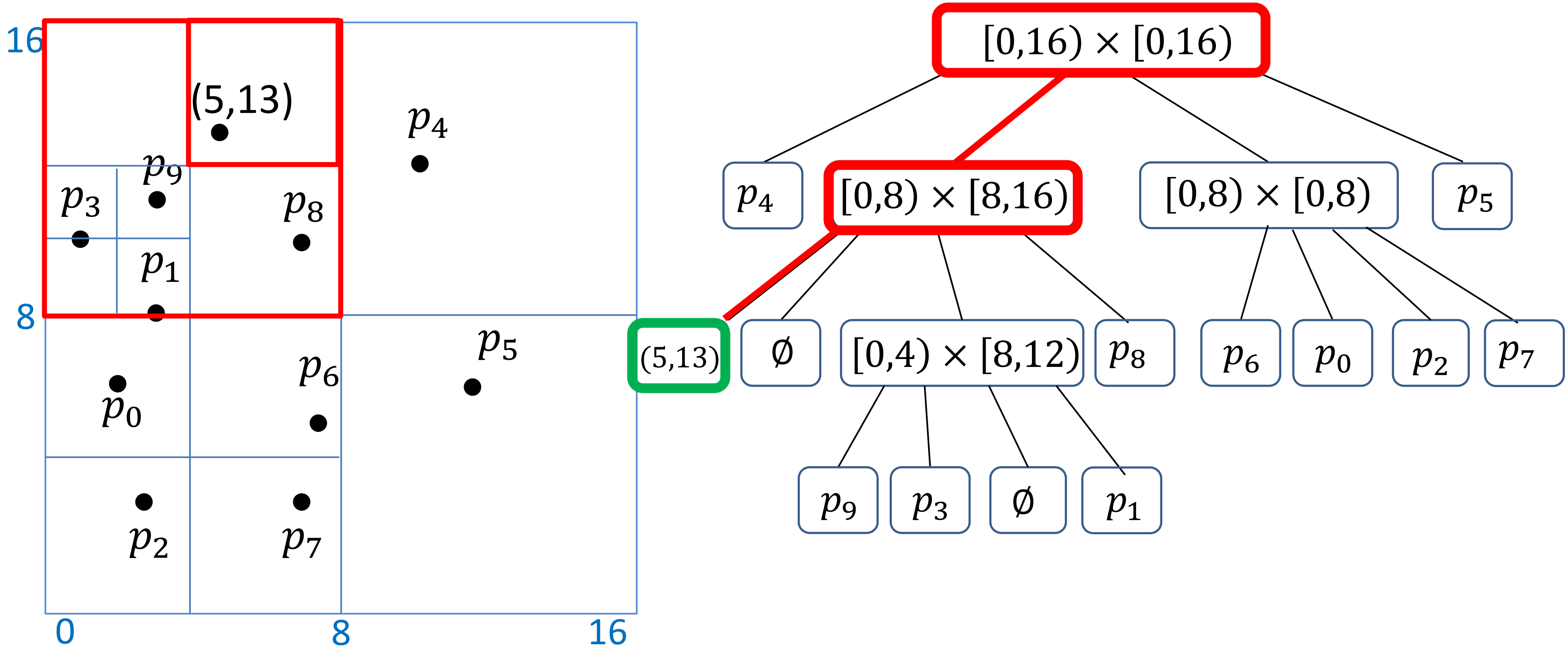




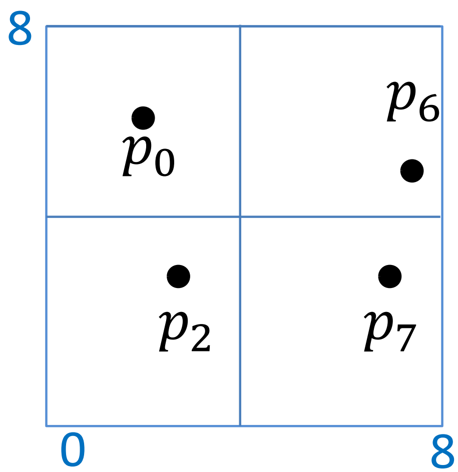
- First perform search
- Two cases
    1. search finds a leaf storing one point
    2. search finds an empty leaf
        - example: insert (5,13)

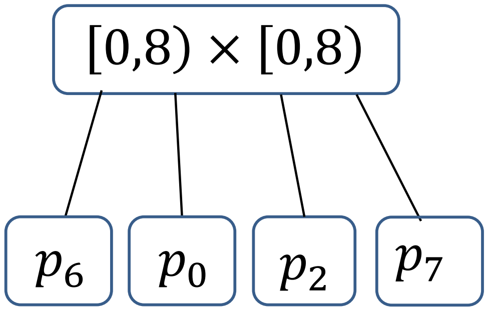
Quadtree Insert



- First perform search
- Two cases
  1. search finds a leaf storing one point
  2. search finds an empty leaf
     - example: insert(5,13)
     - insert the point into leaf

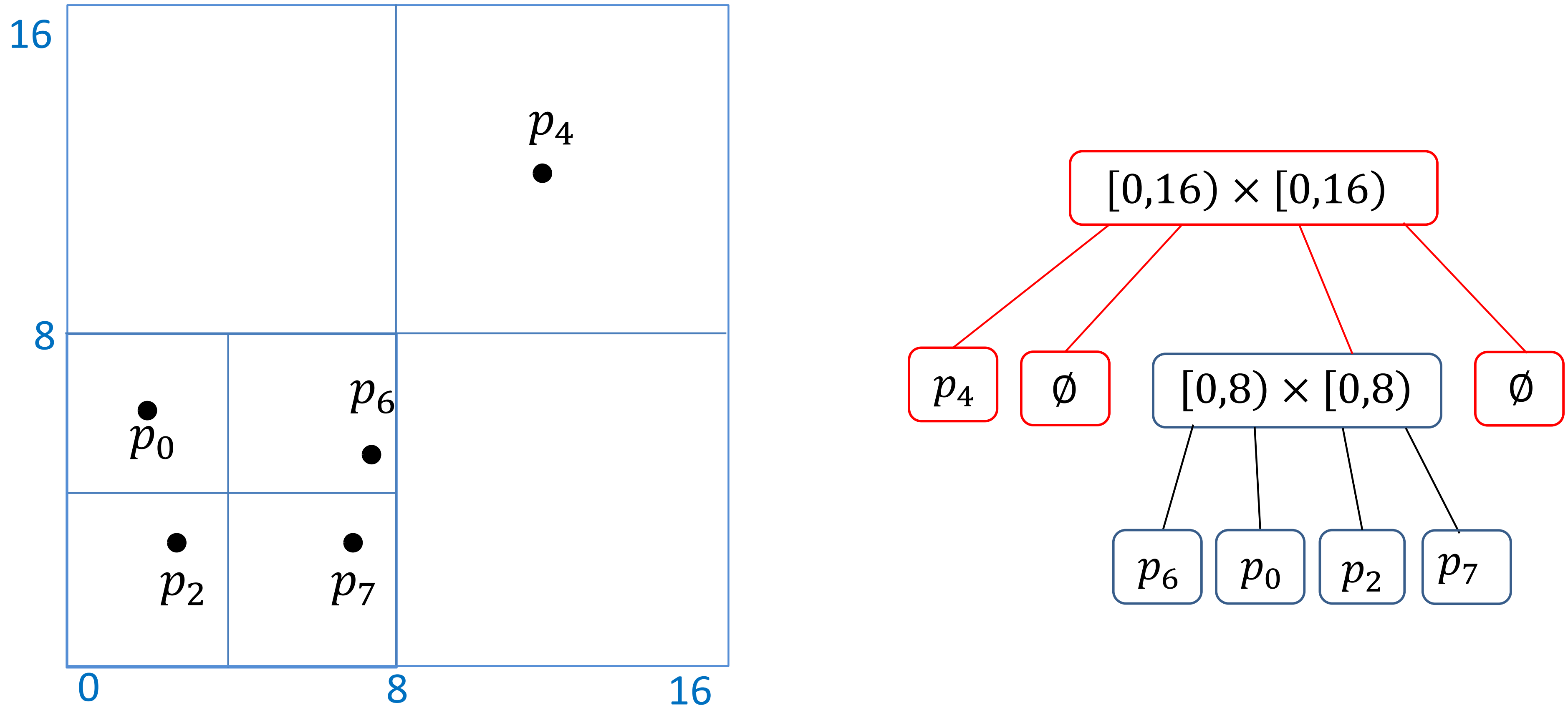
Quadtree Insert





- If we insert point outside the bounding box, no need to rebuild the part corresponding to the old tree, it becomes subtree in the new tree
    - due to bounding box being $[0, 2^k) \times [0, 2^k)$

Quadtree Insert



- If we insert point outside the bounding box, no need to rebuild the part corresponding to the old tree, it becomes subtree in the new tree
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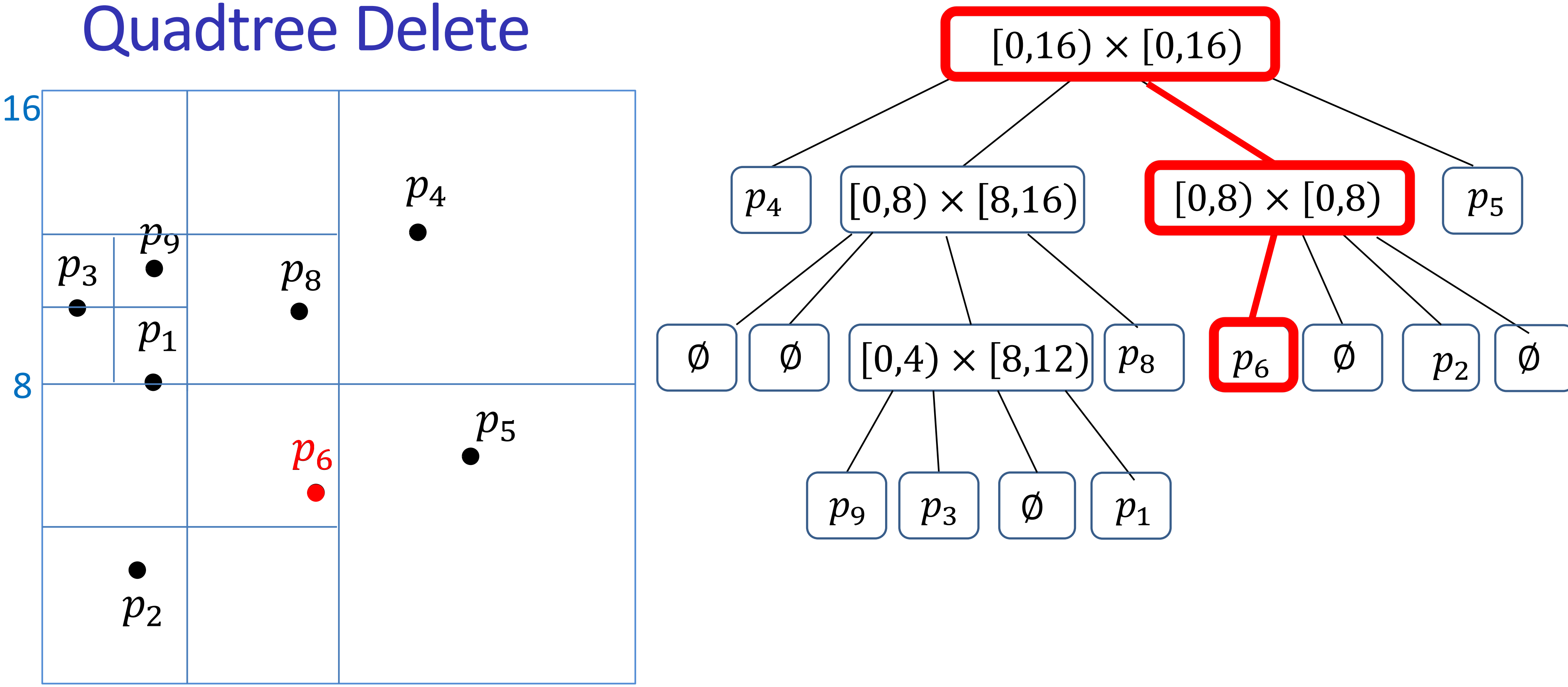
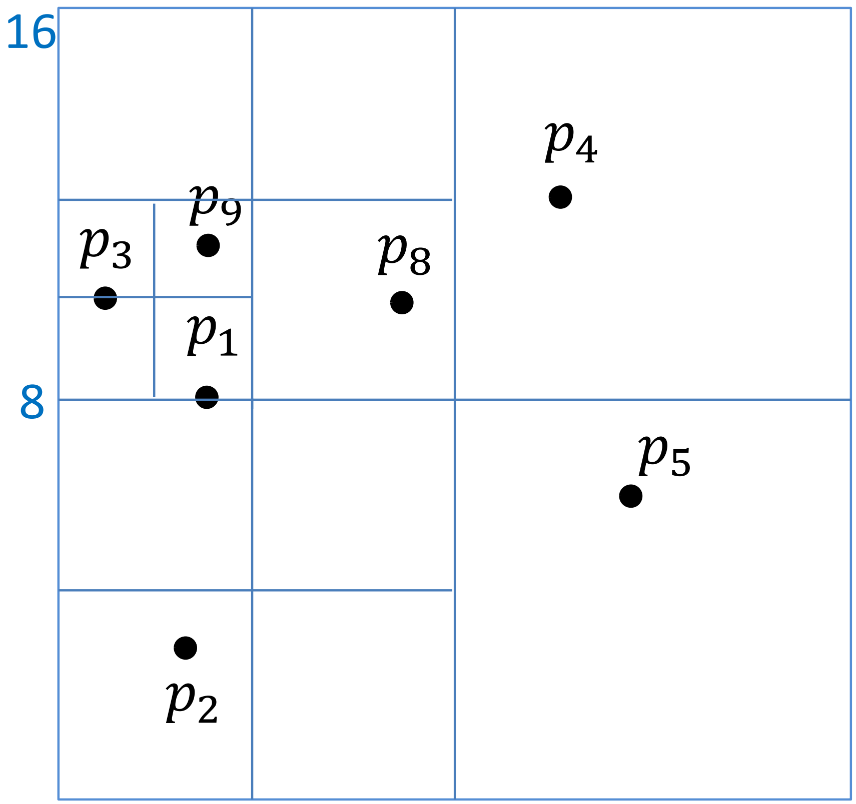
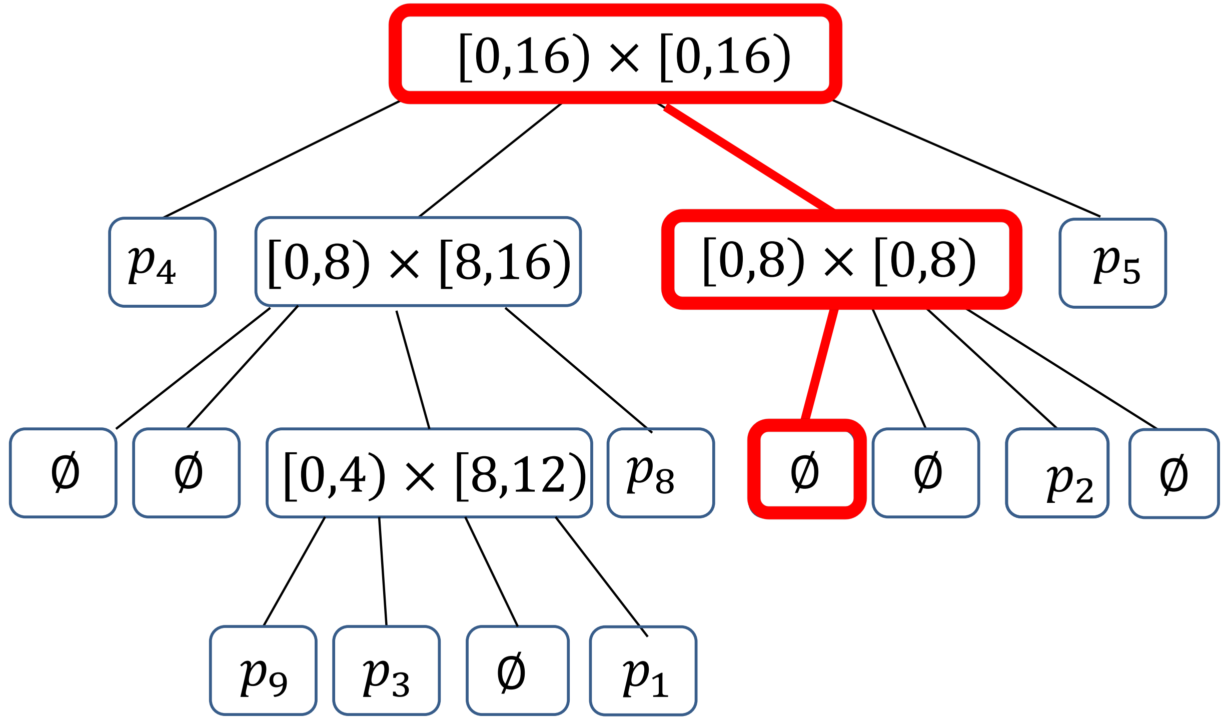
Quadtree Delete



- search will find a leaf containing the point
  - example: delete(p_6)
- remove the point leaving the leaf empty

Quadtree Delete





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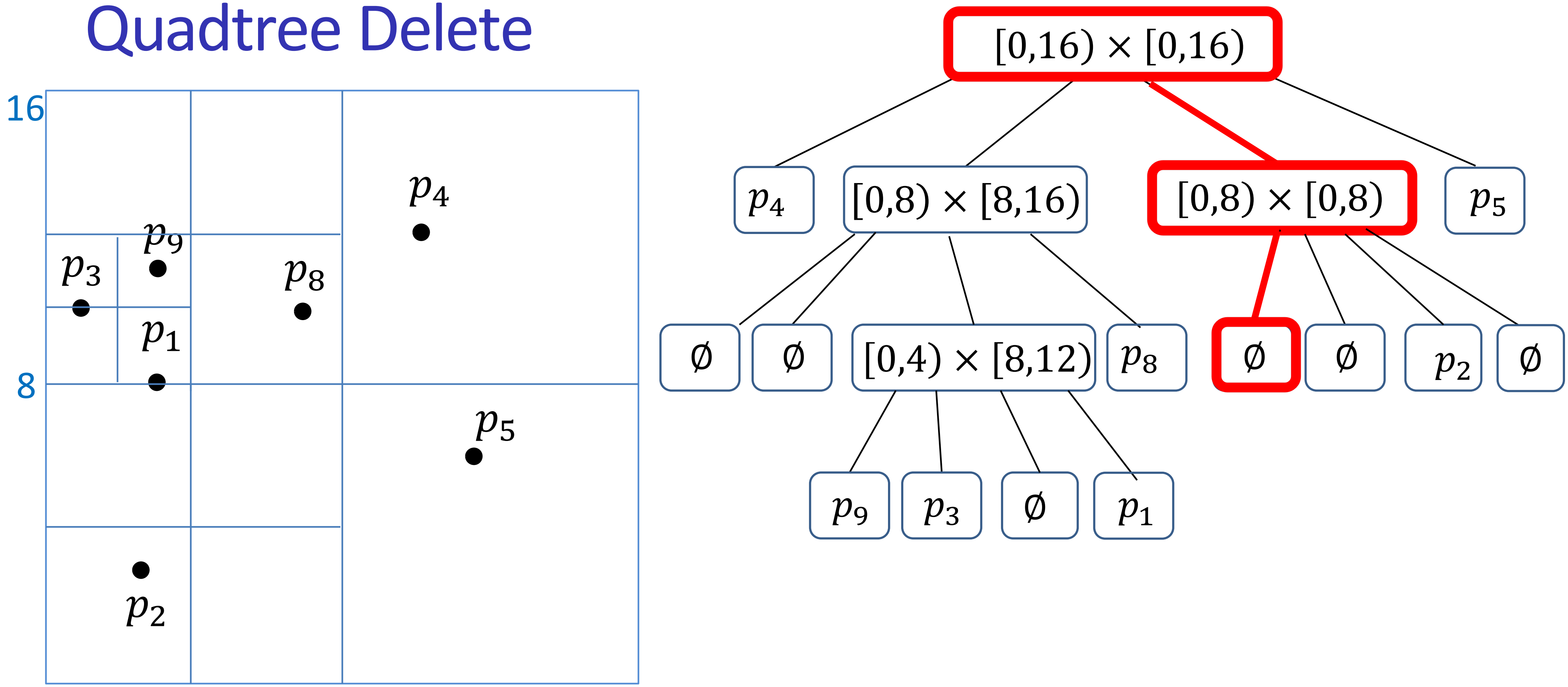
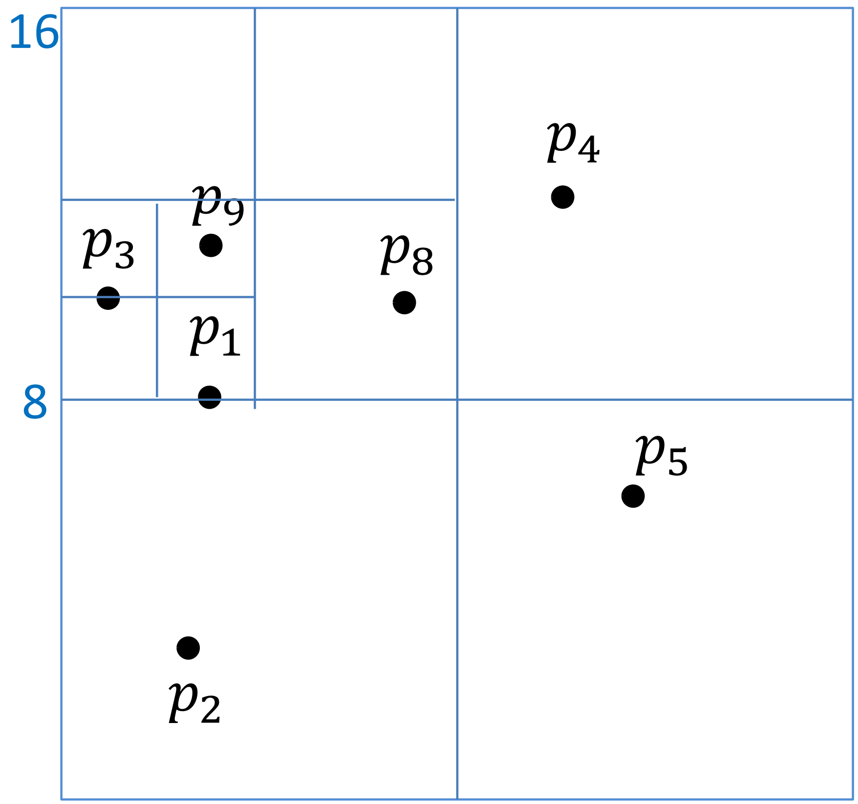
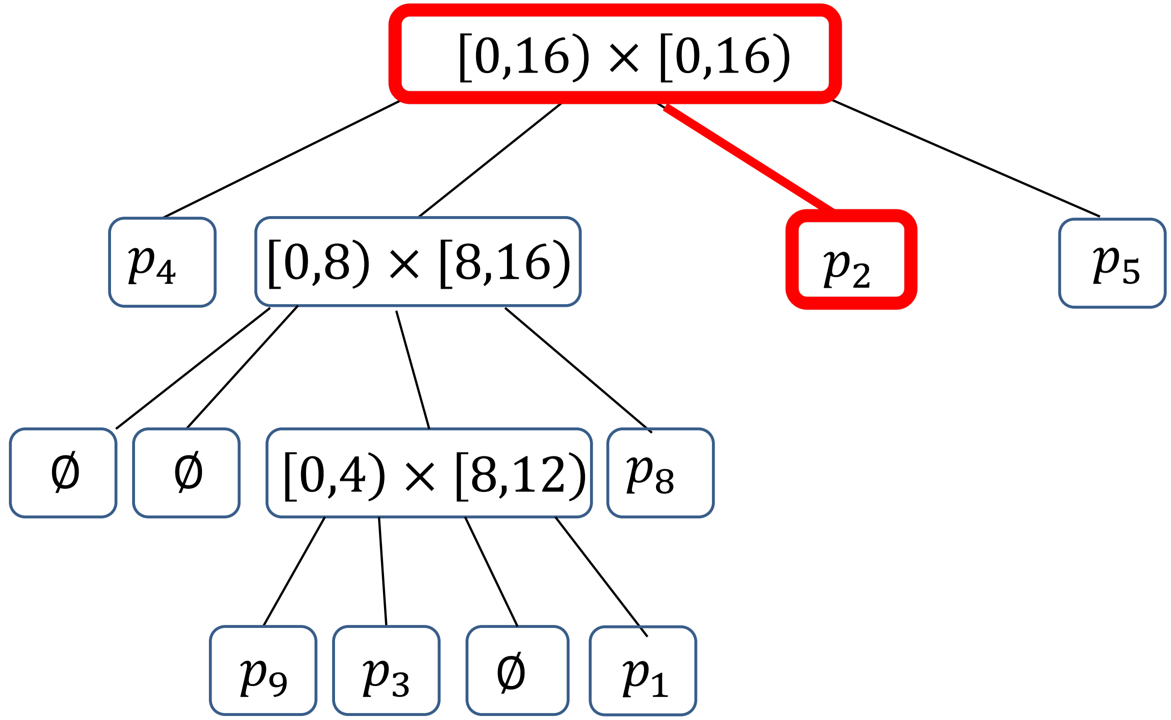
Quadtree Delete



- search will find a leaf containing the point
  - example: delete(p_6)
- remove the point leaving the leaf empty
- if parent now stores only one point in its region
  - make parent node into a leaf storing its only child

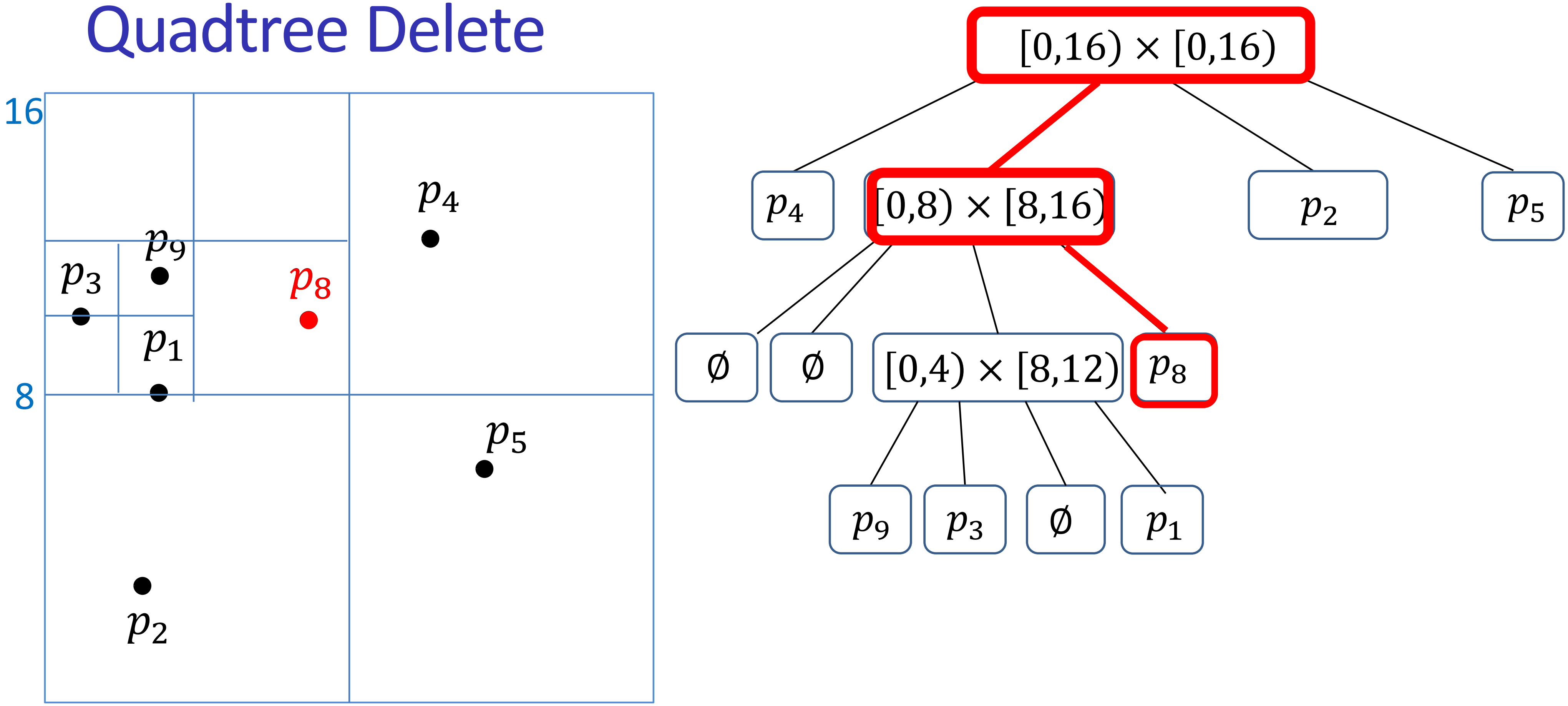
Quadtree Delete





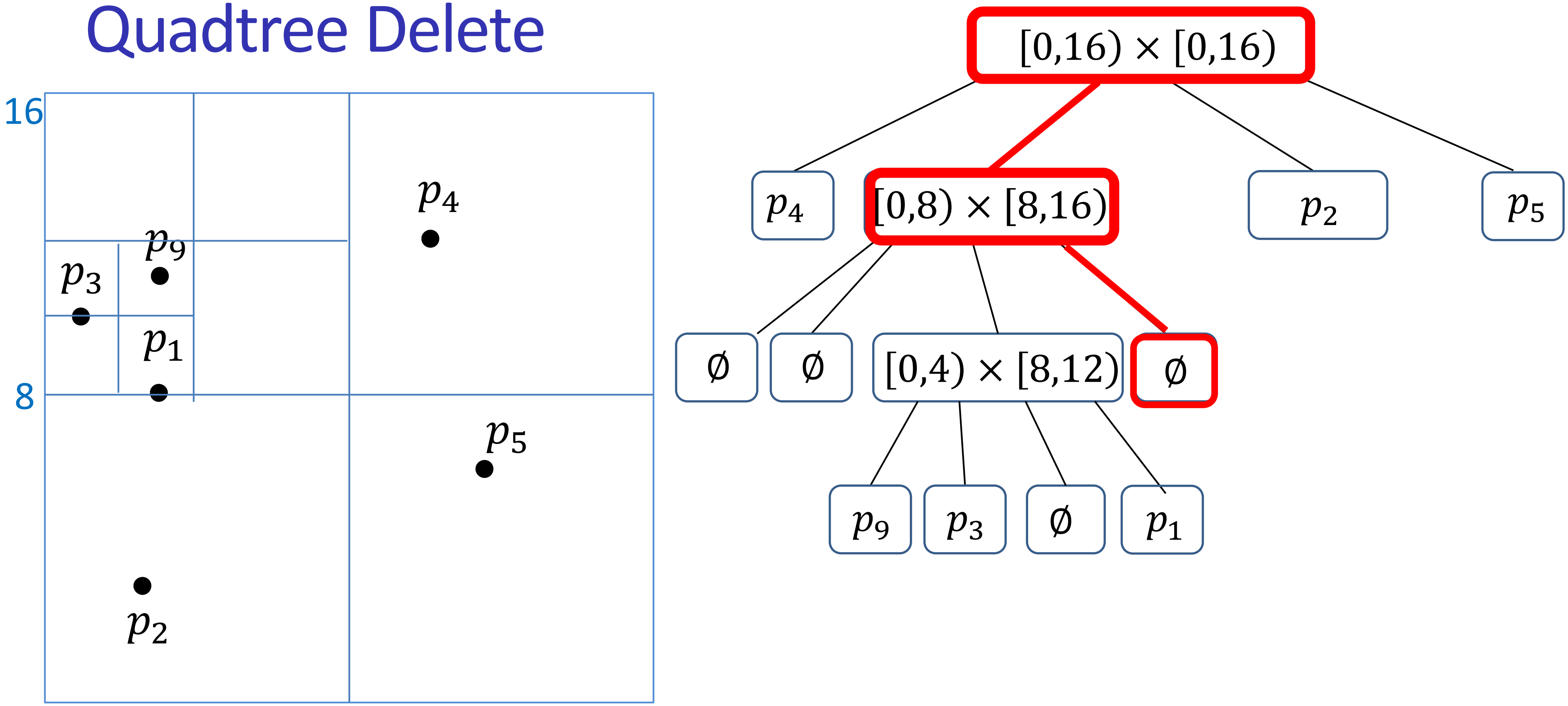
- search will find a leaf containing the point
    - example: delete(p_6)
- remove the point leaving the leaf empty
- if parent now stores only one point in its region
    - make parent node into a leaf
    - check up the tree, repeating making any parent with only 1 point into a leaf

Quadtree Delete



- Another example: delete(p_8)

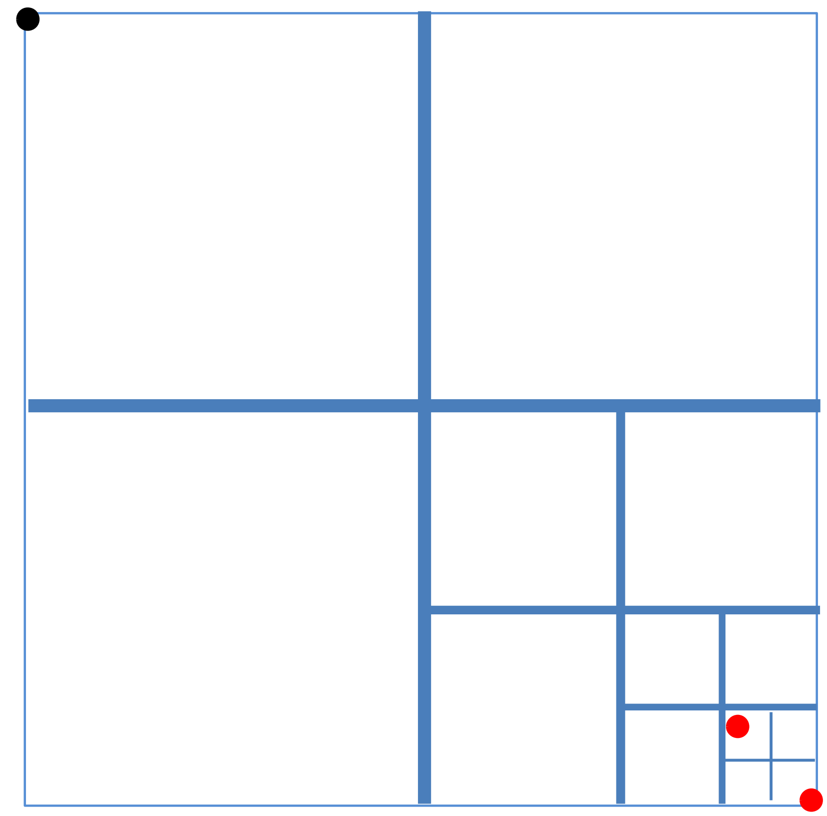
Quadtree Delete



- Do not make parent into a leaf as it stores multiple points

Quadtree Analysis

$$\text{height} = 4$$



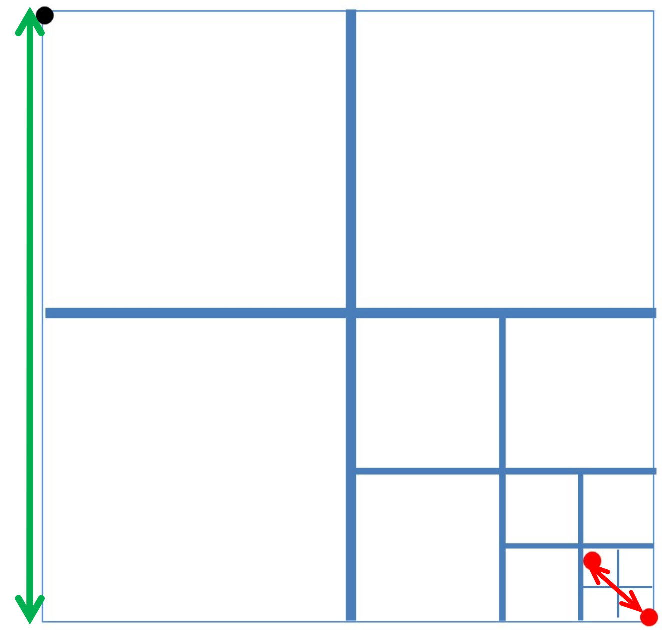
- Search, insert, delete depend on quadtree height
- What is the height of a quadtree?
  - can have very large height for bad distributions of points
  - example with just three points
  - can make height arbitrarily large by moving red points closer together

Quadtree Analysis

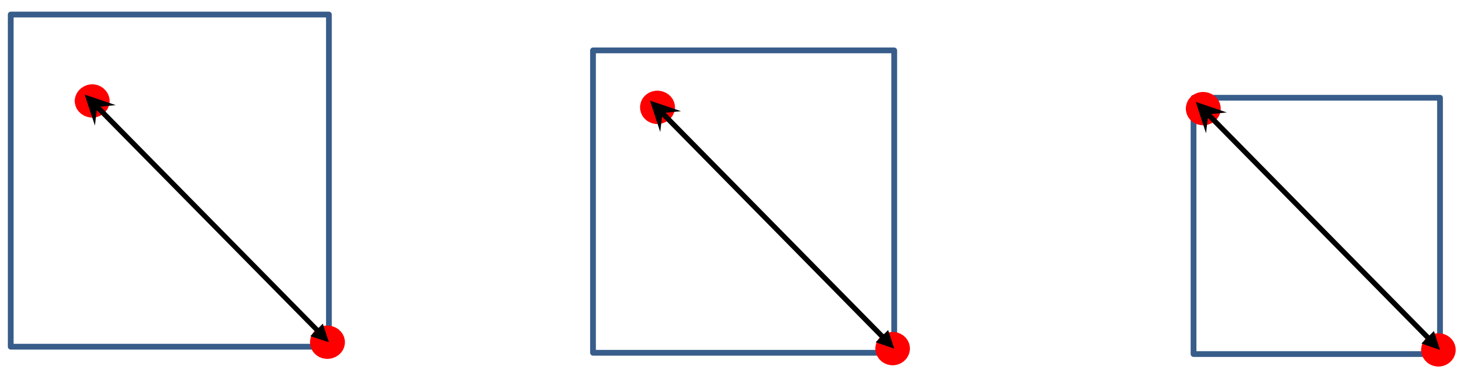
- spread factor of points S

$$\rho(S) = \frac{L}{d_{min}}$$

  - $L =$ side length of R
  - d_{min} is smallest distance between two points in S
- Worst case: height $h \in \Omega(\log \rho(S))$

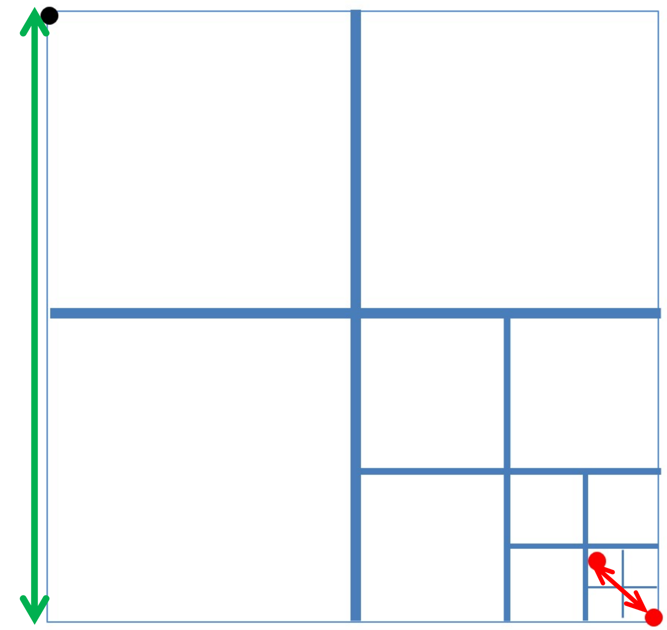


red points are at at distance d_{min} from each other



- While smallest region diagonal is $\geq d_{min}$, 2 red points are in same region

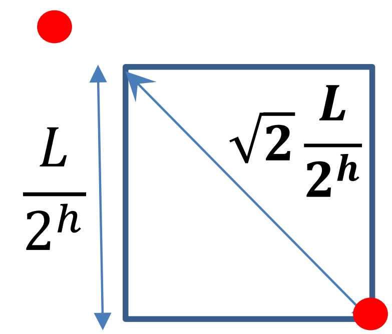
Quadtree Analysis



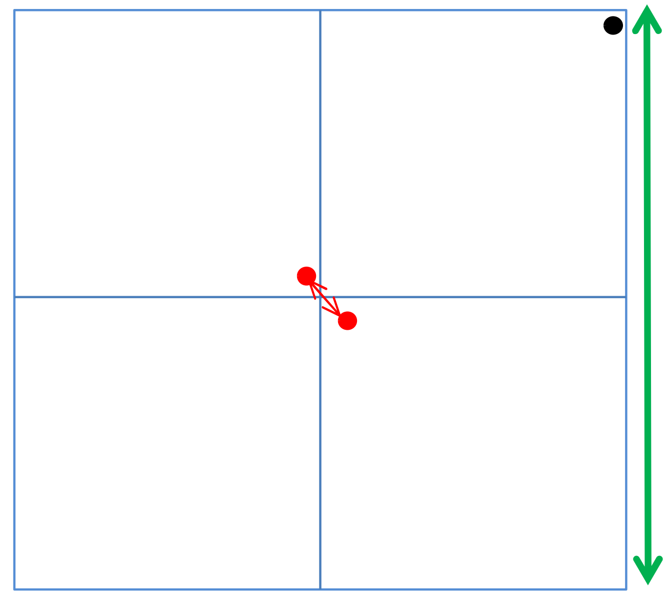
- spread factor of points S

$$\rho(S) = \frac{L}{d_{min}}$$

  - $L =$ side length of R
  - d_{min} is smallest distance between two points in S
- Worst case: height $h \in \Omega(\log \rho(S))$
  - while smallest region diagonal is $\geq d_{min}$, 2 red points are in same region
  - if height is h, then we do h rounds of subdivisions
  - after h subdivisions, smallest regions have side length $\frac{L}{2^h}$
  - diagonal in smallest region is $\sqrt{2}\frac{L}{2^h}$
  - smallest region contains one red point $\Rightarrow \sqrt{2}\frac{L}{2^h} < d_{min}$
  - rearrange: $\sqrt{2}\frac{L}{d_{min}} < 2^h$
  - take log of both sides: $h > \log\left(\sqrt{2}\frac{L}{d_{min}}\right) = \log\left(\sqrt{2}\rho(S)\right)$



Quadtree Analysis



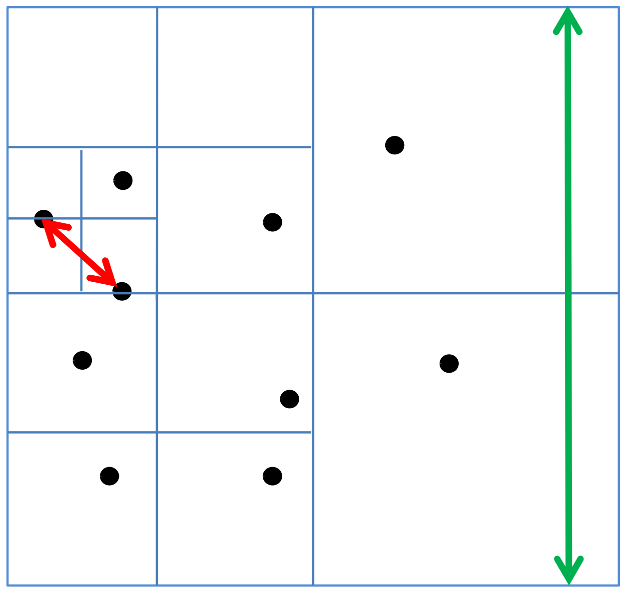
- spread factor of points S

$$\rho(S) = \frac{L}{d_{min}}$$

  - $L =$ side length of R
  - d_{min} is smallest distance between two points in S

- In the ***worst*** case, height $h \in \Omega(\log \rho(S))$
- However, height can be much better even if the spread is arbitrarily large

Quadtree Analysis

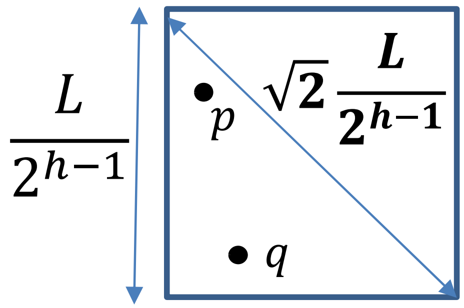


- spread factor of points S

$$\rho(S) = \frac{L}{d_{min}}$$

  - $L =$ side length of R
  - d_{min} is smallest distance between two points in S

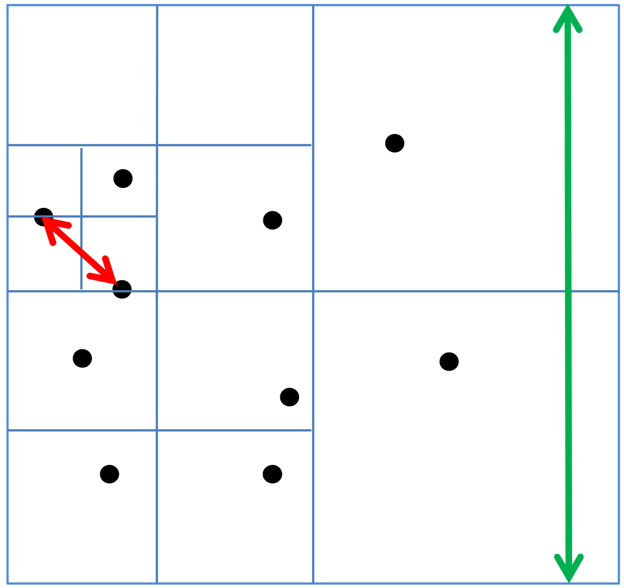
- In the worst case, height $h \in \Omega(\log \rho(S))$
- In **any case**, height $h \in O(\log \rho(S))$
  - let v be an internal node at depth $h-1$
    - there are at lest 2 points p, q inside its region
      - $d_{min} \leq d(p,q)$
    - the corresponding region has side length $\frac{L}{2^{h-1}}$
    - maximum distance between 2 points in such region is $\sqrt{2}\frac{L}{2^{h-1}}$



$$d_{min} \leq d(p,q) \leq \sqrt{2}\frac{L}{2^{h-1}}$$

$$2^{h-1} \leq \sqrt{2}\frac{L}{d_{min}} = \sqrt{2}\,\rho(S) \Rightarrow h \leq 1 + \log(\sqrt{2}\rho(S))$$

Quadtree Analysis



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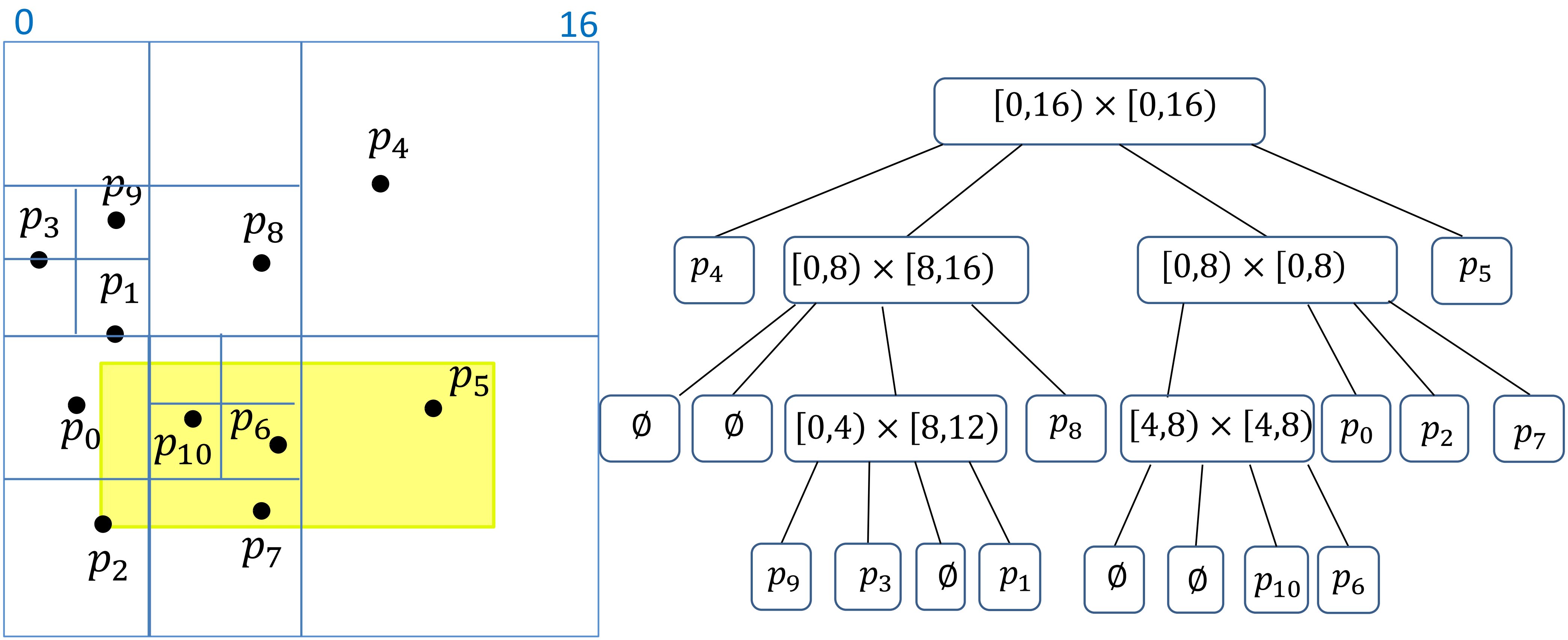
  - $L =$ side length of R
  - d_{min} is smallest distance between two points in S

- In the worst case, height $h \in \Omega(\log \rho(S))$
- In any case, height $h \in O(\log \rho(S))$
  - to guarantee good performance, $\log \rho(S)$ should be much smaller than n
- Complexity to build initial tree: $\Theta(nh)$ worst-case
  - expensive if large height (as compared to the number of points)

Quadtree Range Search Example



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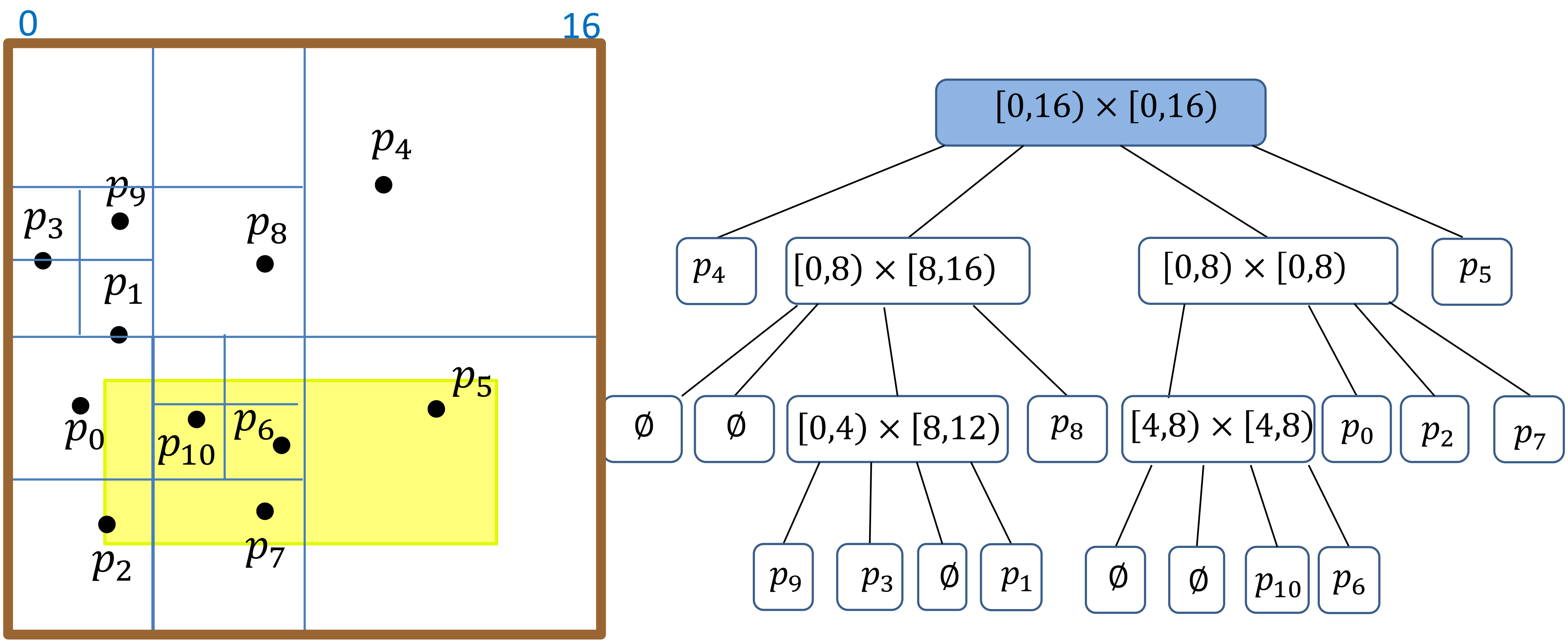

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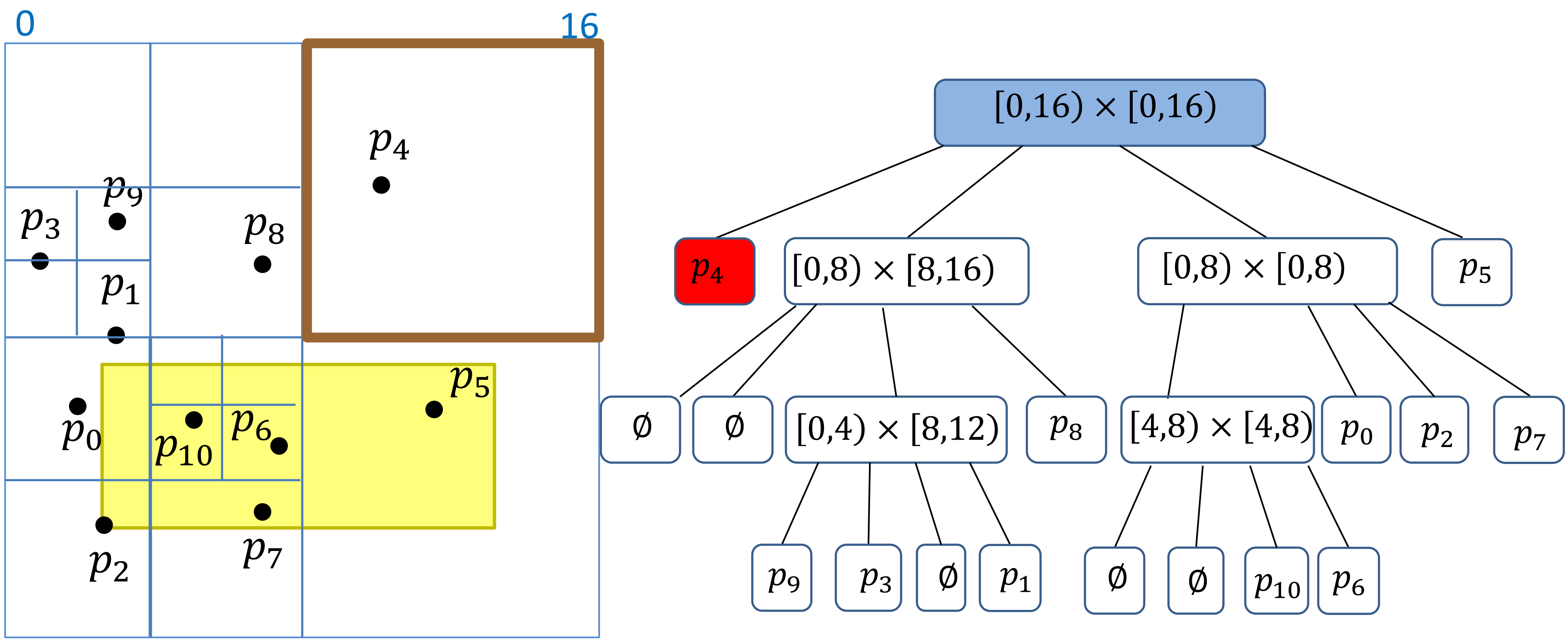

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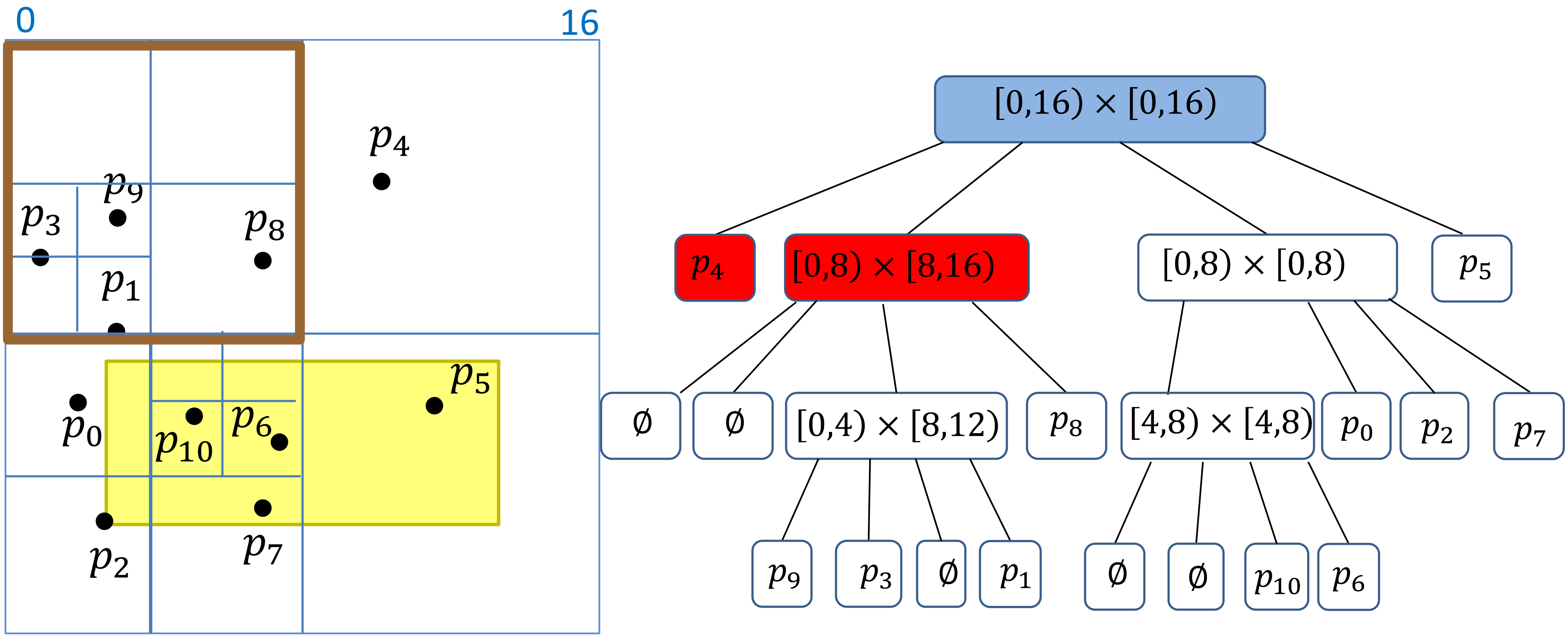

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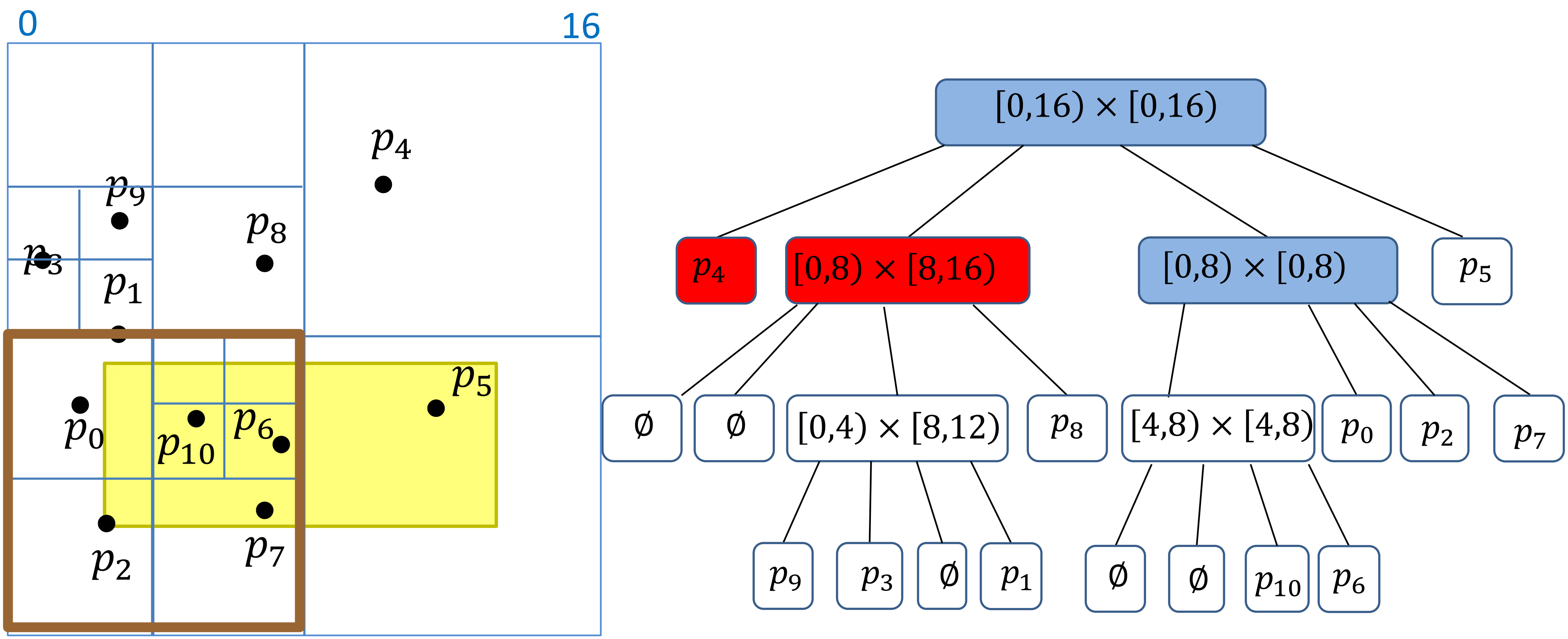

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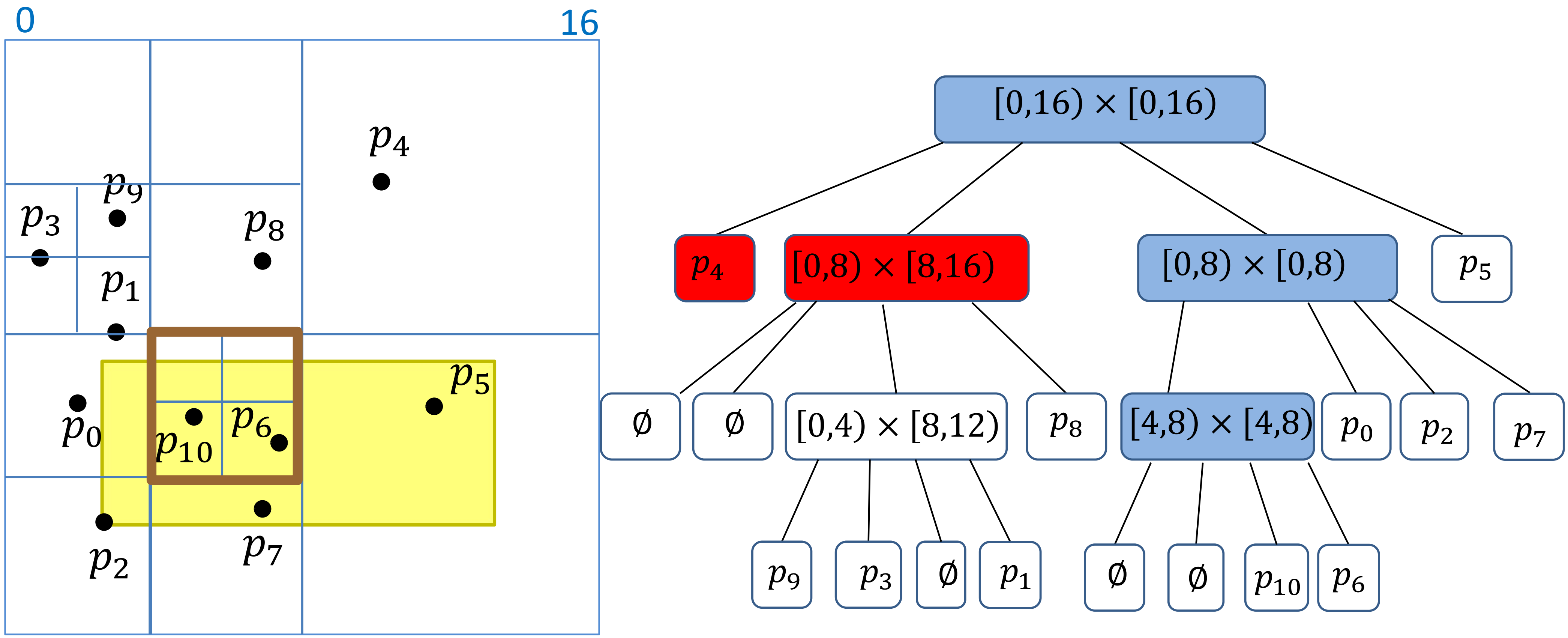

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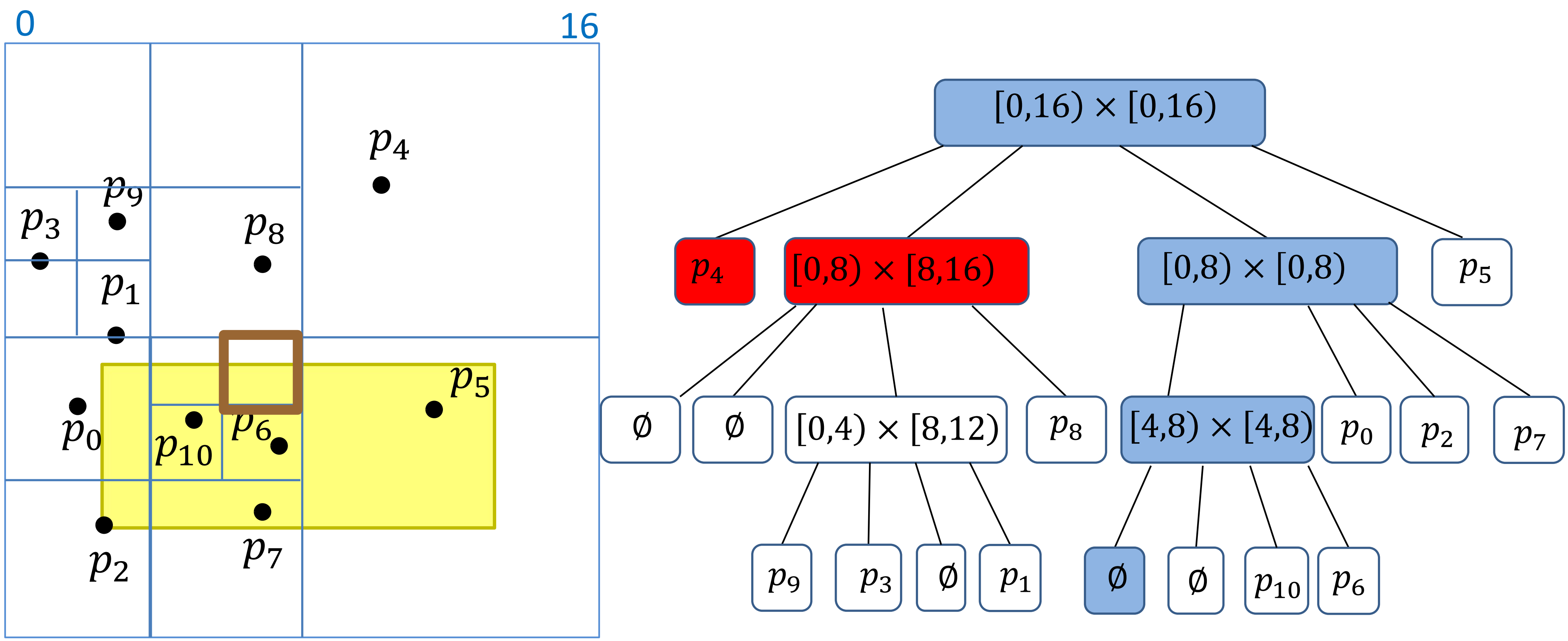

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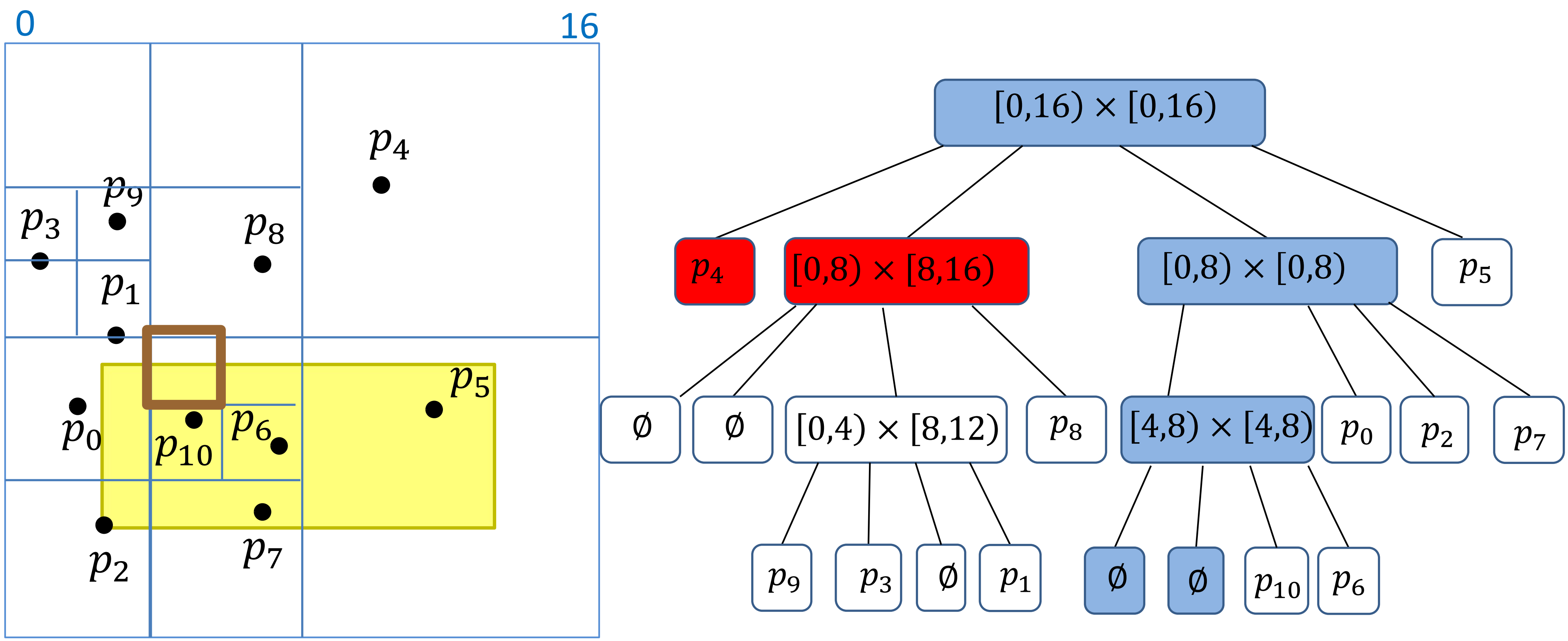

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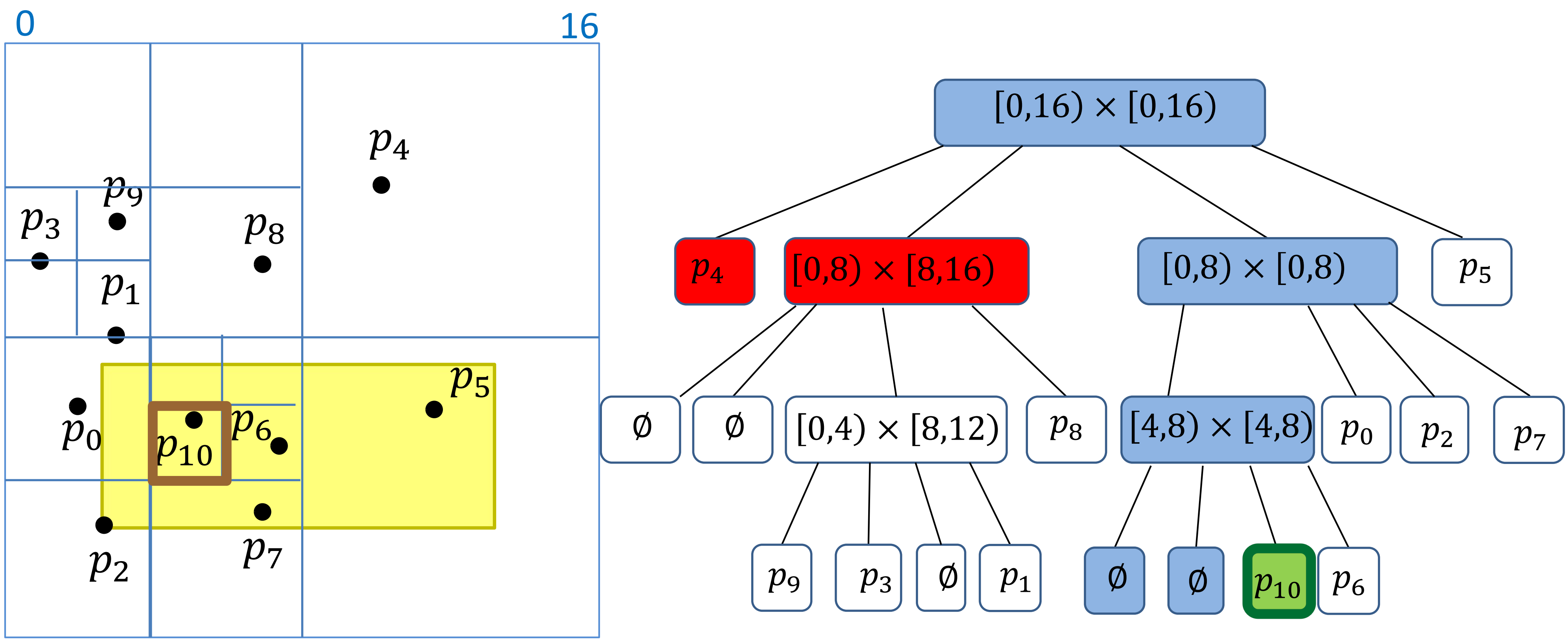

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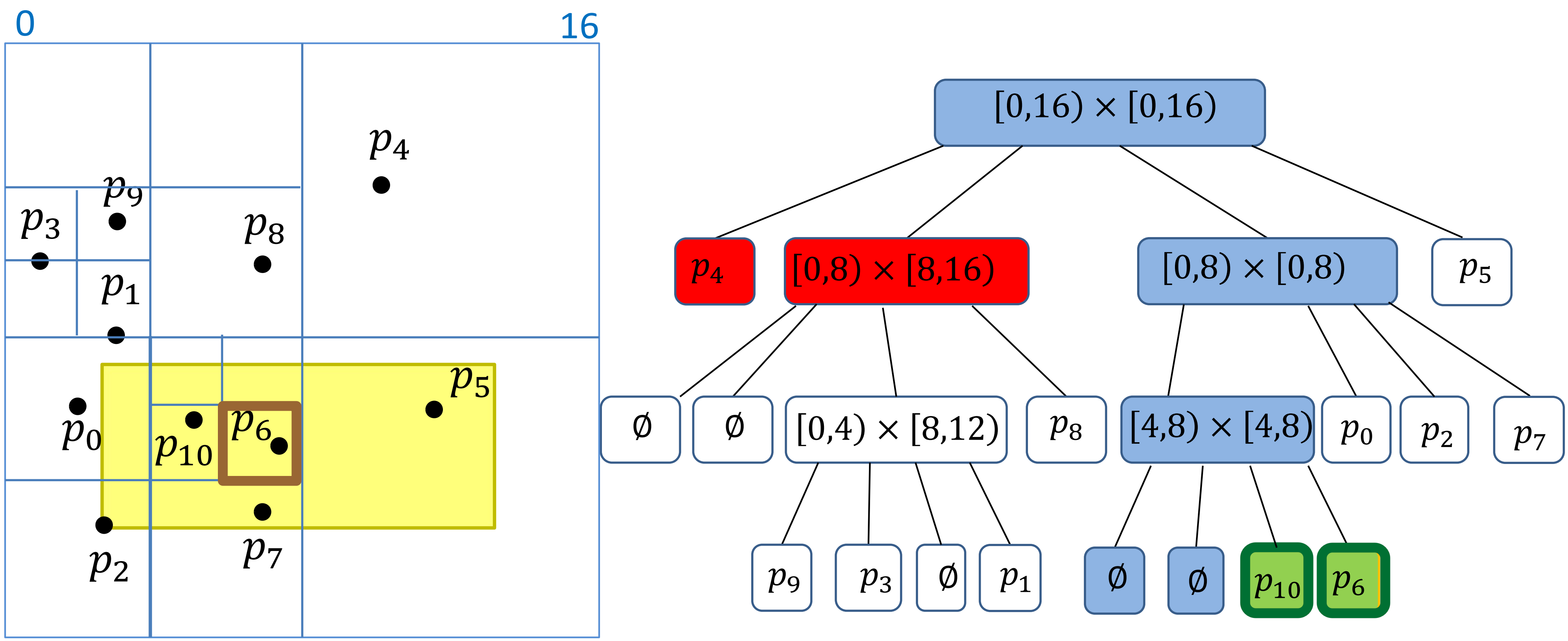

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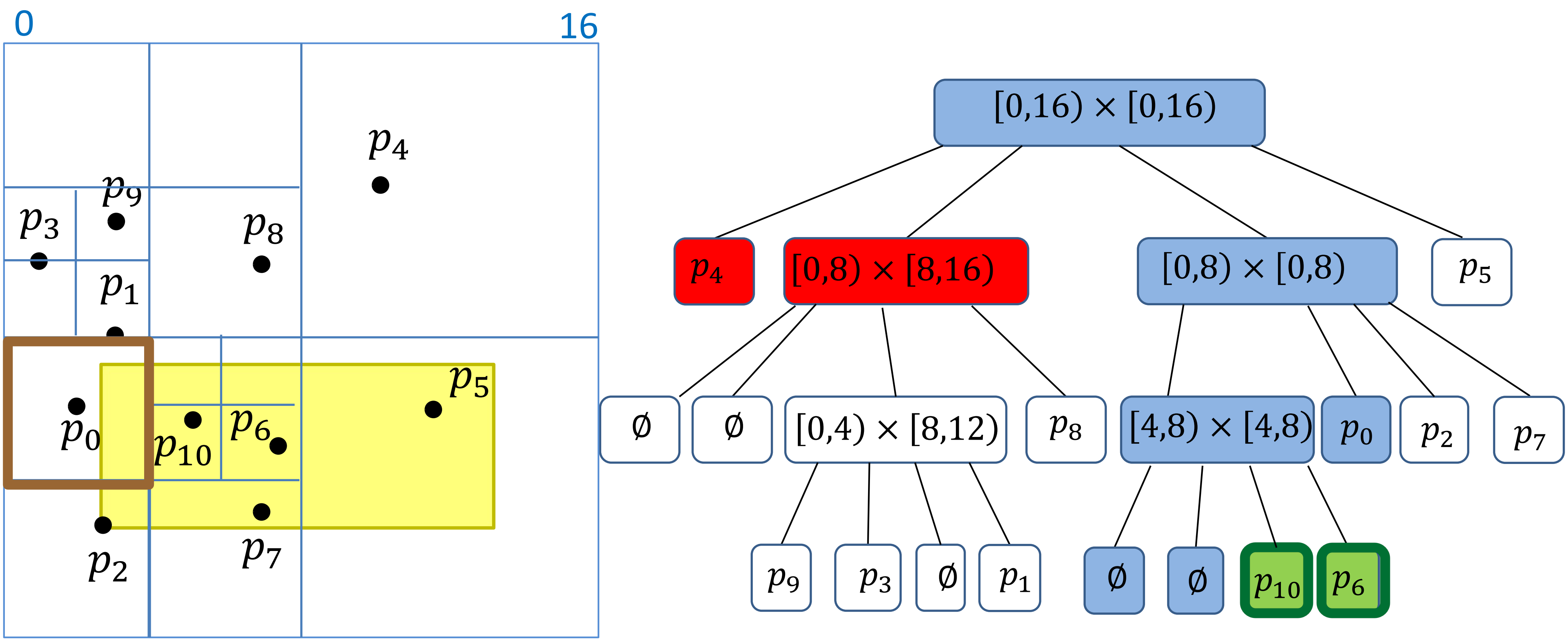

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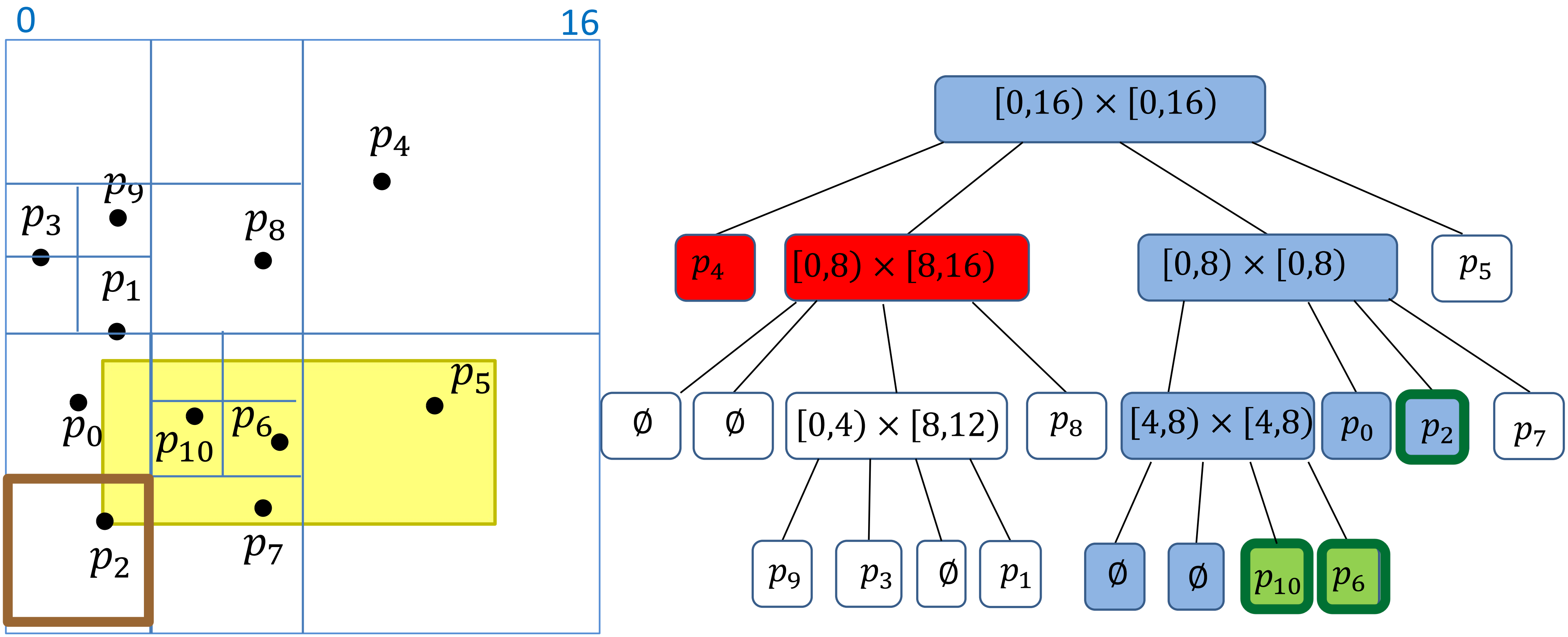

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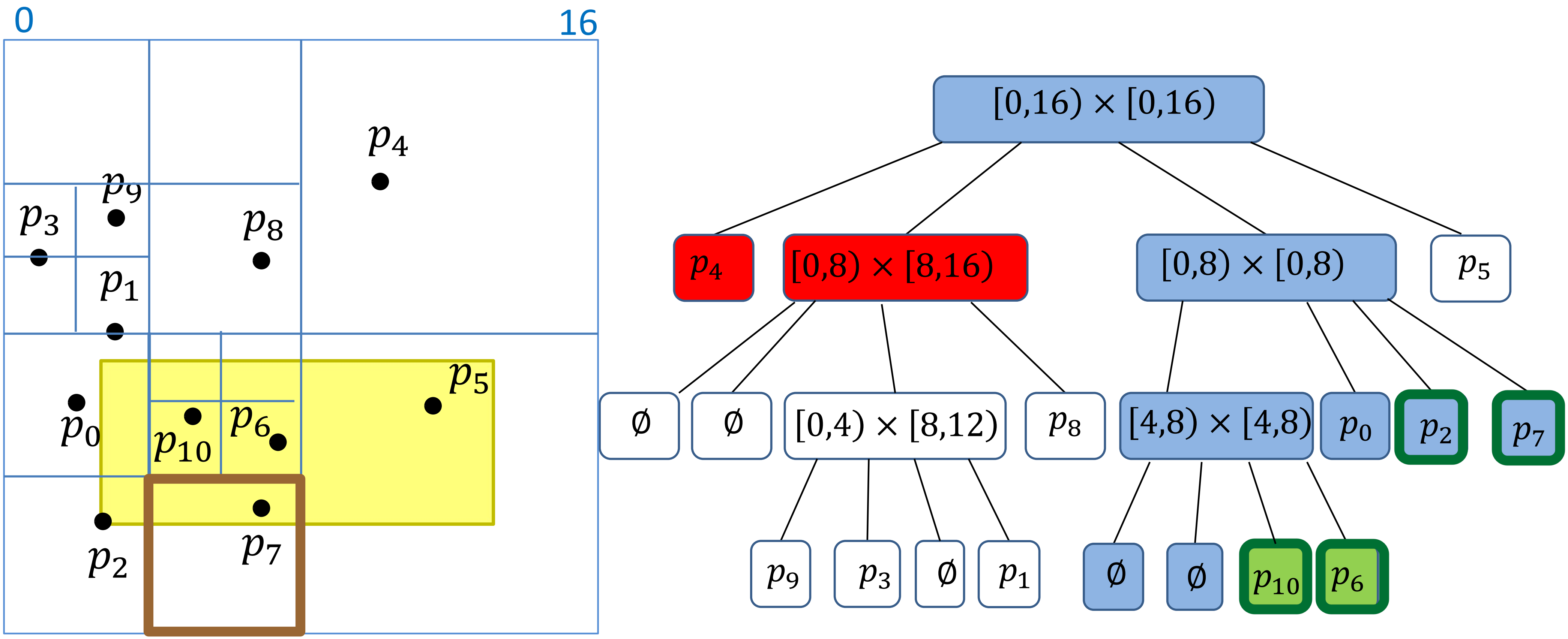

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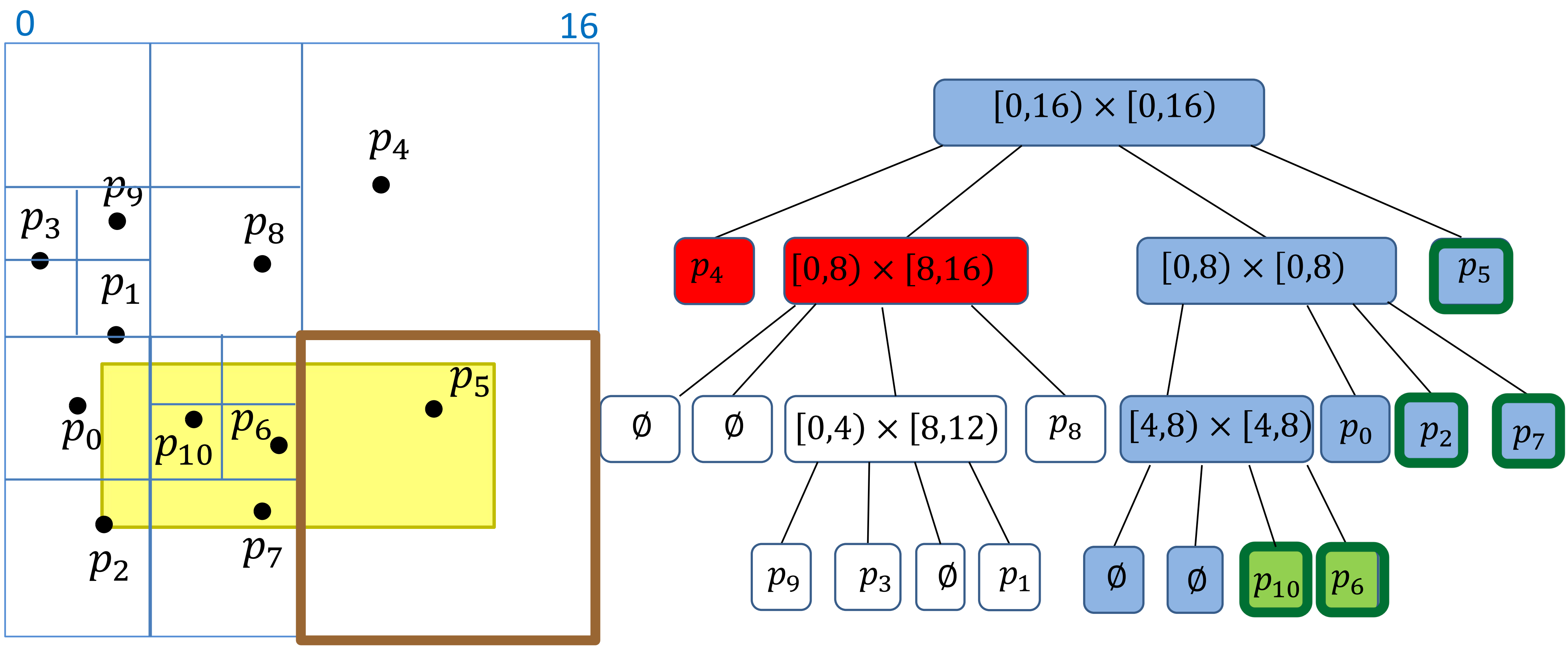

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Quadtree Range Search

Qtree::RangeSearch$(r \leftarrow root, Q)$
r : quadtree root, Q: query rectangle

```
let R be the region associated with r
if R ⊆ Q  then      //inside node, stop search
    report all points below r
    return
if R ∩ Q = ∅ then //outside node, stop search
    return
// boundary node, recurse if not a leaf
if r is a leaf  then // leaf, do not recurse
    p ← point stored at r
    if p is not NULL and in Q return p
    else return
for each child v of r do
    QTree-RangeSearch(v, Q)
```

- $R \subseteq Q, R \cap Q = \emptyset$ computed in constant time from coordinates of R, Q
- Code assumes each quadtree node stores the associated square
- Alternatively, these could be re-computed during search
    - space-time tradeoff

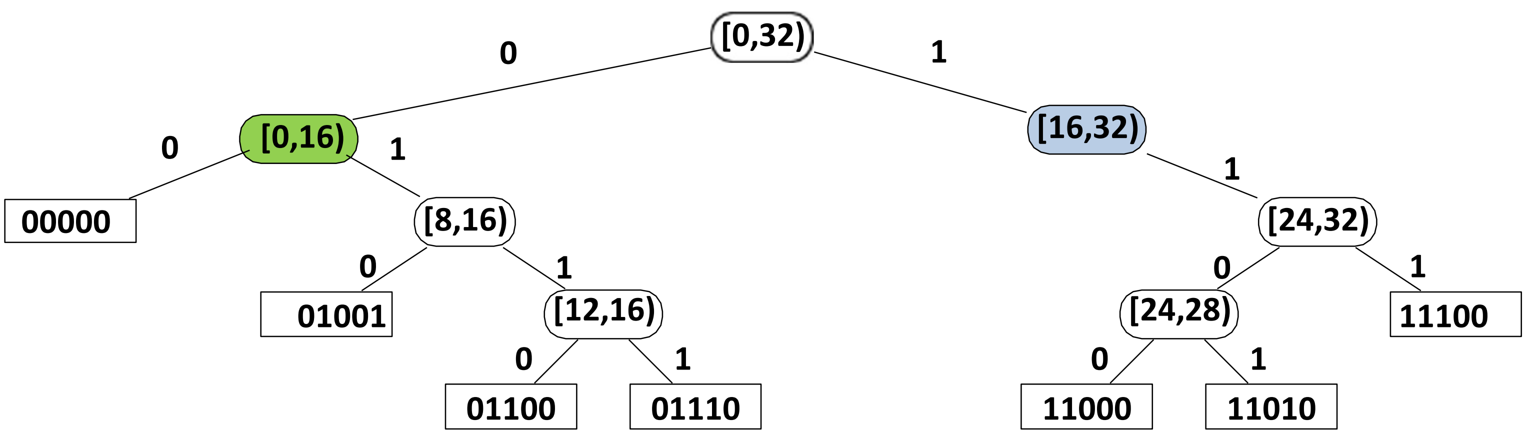
RangeSearch Analysis

- Running time is number of visited nodes + output size
- No good bound on number of visited nodes
  - may have to visit nearly all nodes in the worst case
  - $\Theta(nh)$ worst-case
    - this is worse than exhaustive search
    - even if the range search returns empty result
    - but in practice usually much faster

Quadtrees in other dimensions

points	0	9	12	14	24	26	28
base 2	00000	01001	01100	01110	11000	11010	11100

- Quad-tree of 1-dimensional points



- Same as a pruned trie
  - with splitting stopped once key is unique

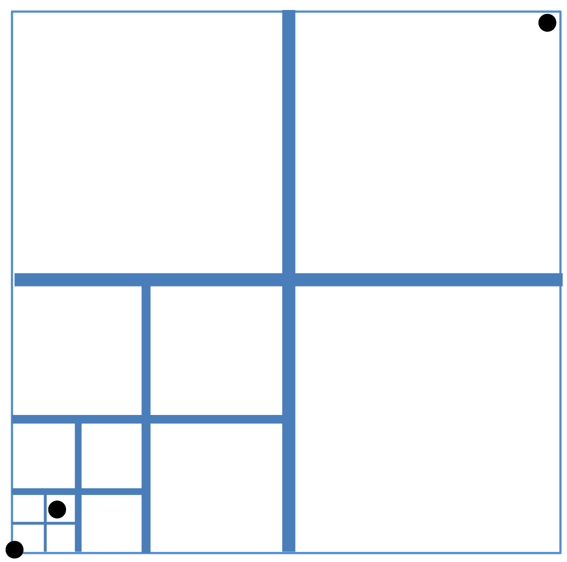
Quadtree summary

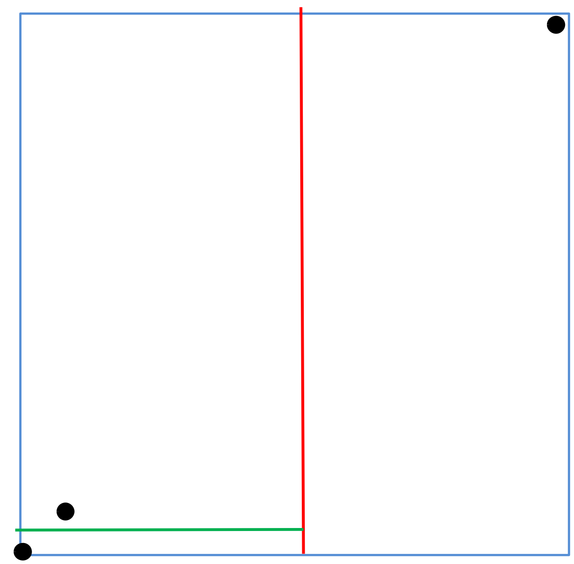
- Quadtrees easily generalize to higher dimensions
  - octrees, *etc.*
  - but rarely used beyond dimension 3
- Easy to compute and handle
- No complicated arithmetic, only divisions by 2
  - bit-shift if the width/height of R is a power of 2
- Space potentially wasteful, but good if points are well-distributed
- Variation
  - stop splitting earlier and allow up to k points in a leaf for some fixed k

Outline

- Range-Searching in Dictionaries for Points
  - Range Search Query
  - Multi-Dimensional Data
  - Quadtrees
  - kd-Trees
  - Range Trees
  - Conclusion

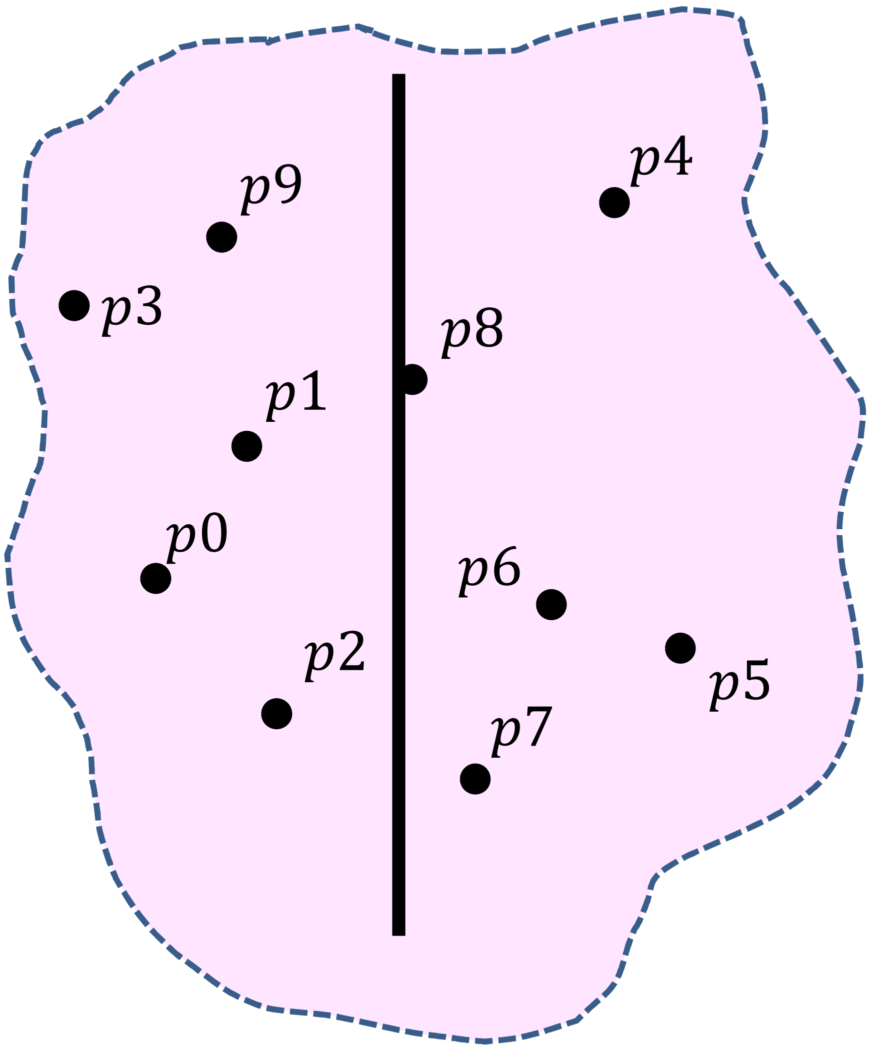
kd-tree motivation





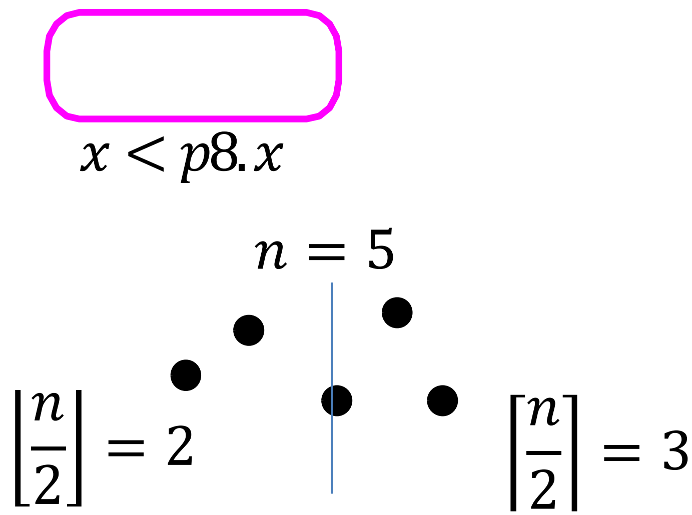
- Quadtree can be very unbalanced
- kd-tree idea
  - split into regions with equal number of points
  - easier to split into two regions with equal number of points (rather than four regions)
  - can split either vertically or horizontally
  - alternating vertical and horizontal splits gives range search efficiency

kd-tree example



$\mathcal{R}^2$ is split into two half regions

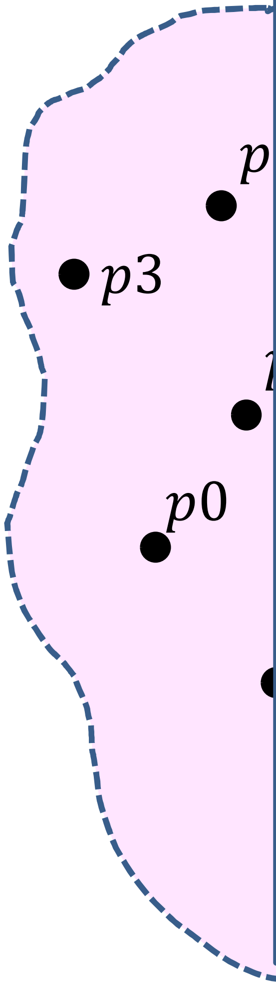
- No need for bounding box
- Root corresponds to the whole $\mathcal{R}^2$
- First find the best vertical split
- $\left\lfloor \frac{n}{2} \right\rfloor$ on one side and $\left\lceil \frac{n}{2} \right\rceil$ and points on the other



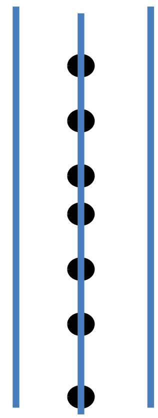
- $m = \left\lfloor \frac{n}{2} \right\rfloor$ in sorted list of x -coordinates
- partition S into $S_{x<m}$ and $S_{x\geq m}$

OV1

kd-tree example



- Because points are in general position, always can split in two equal (or almost equal subsets)
- General position means no two x or y coordinates are the same
- Consider the points below **not** in general position



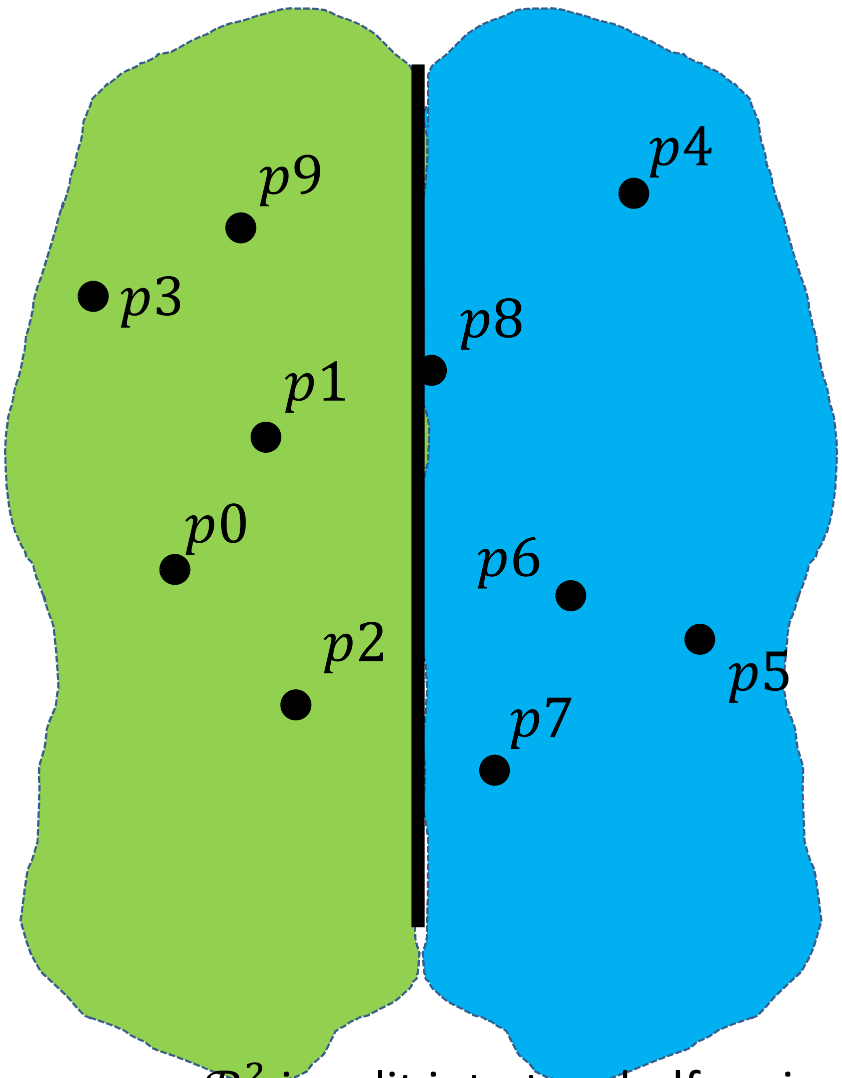
- Cannot divide them in two equal subsets by a vertical line

$\mathcal{R}^2$ is split into two half regions

Slide 62

OV1 Olga Veksler, 3/14/2023

kd-tree example



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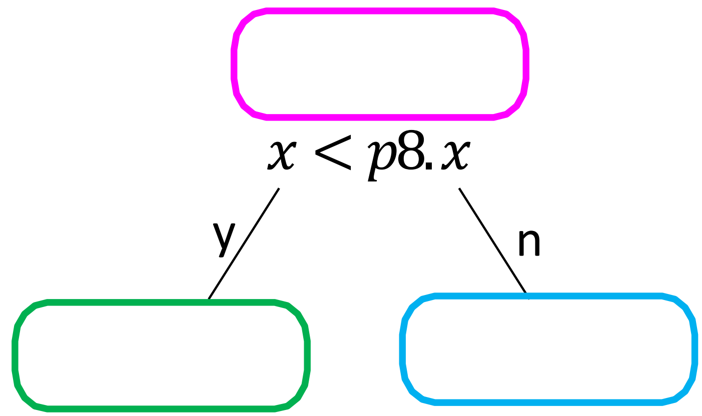

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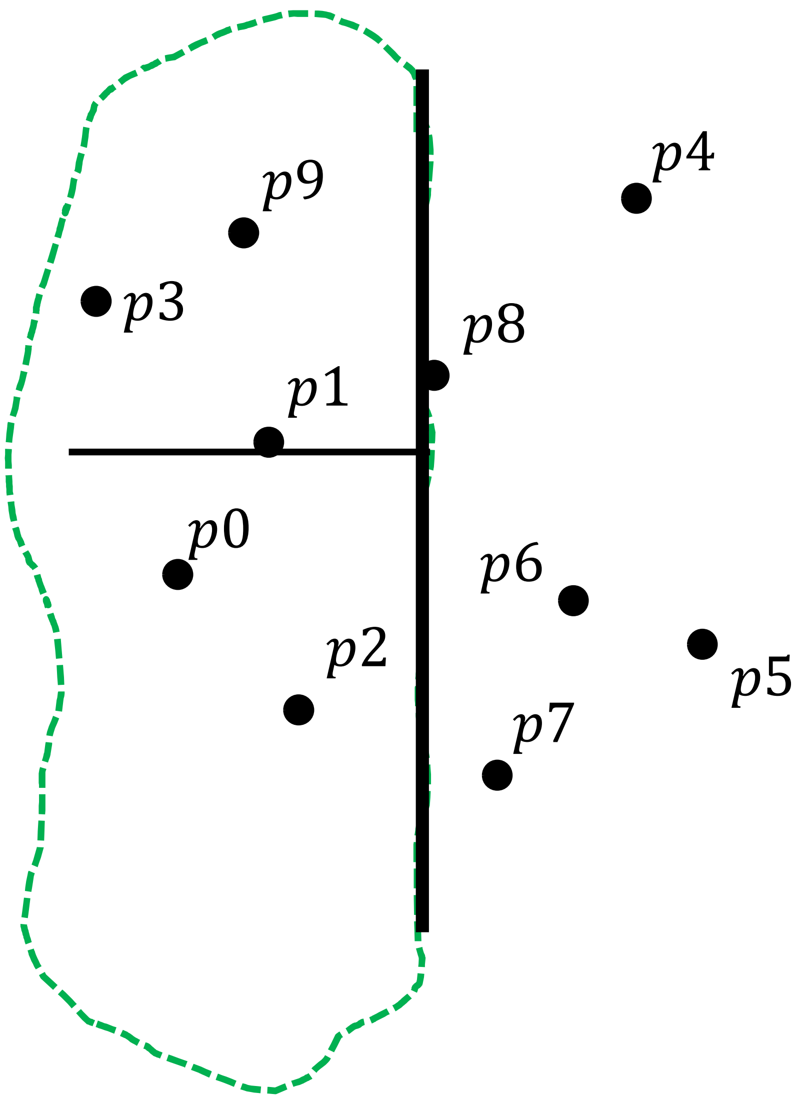
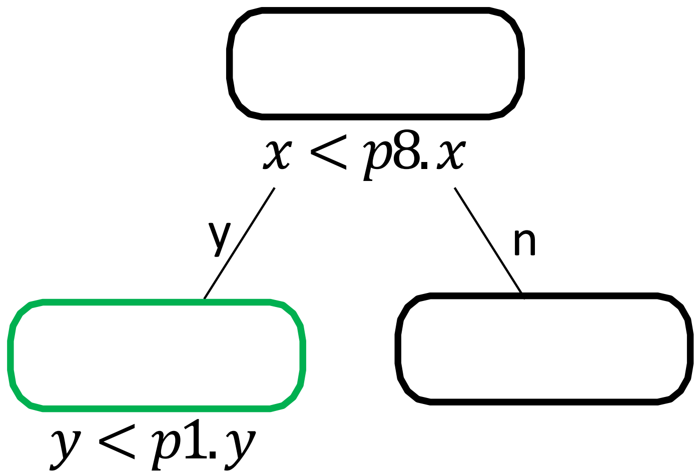


- Recurse on the resulting regions
  - if they have more than one point
- Alternate split direction



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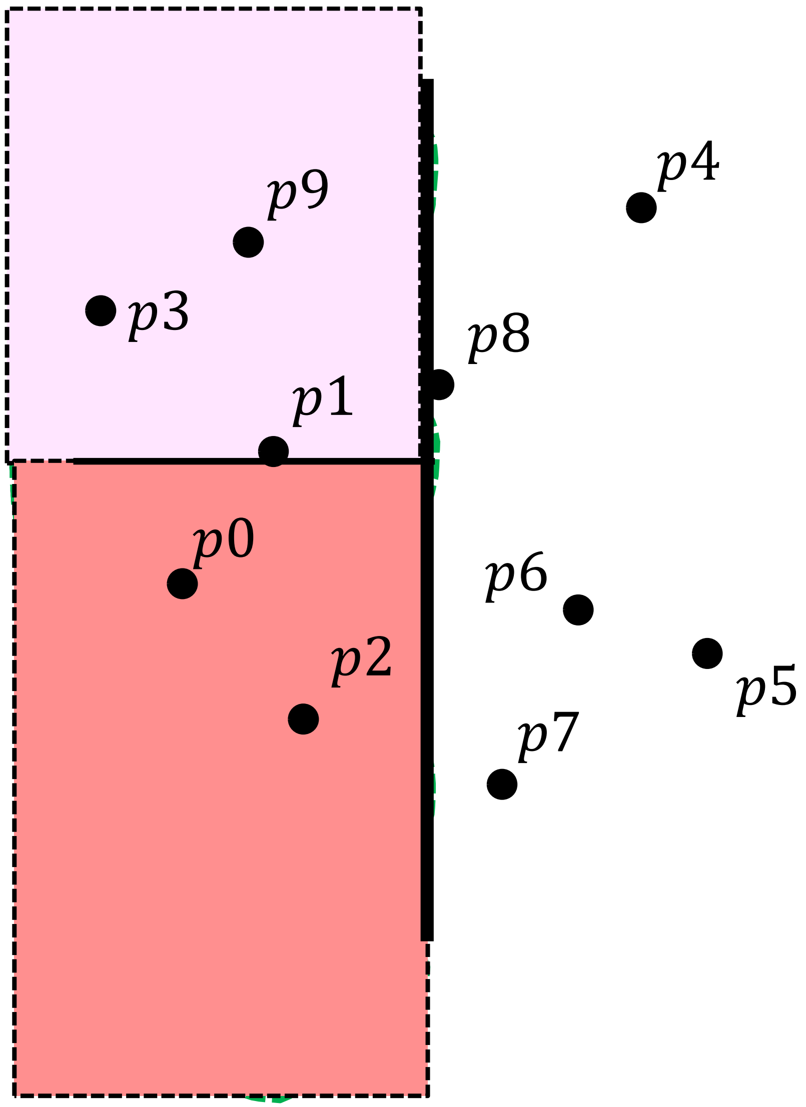

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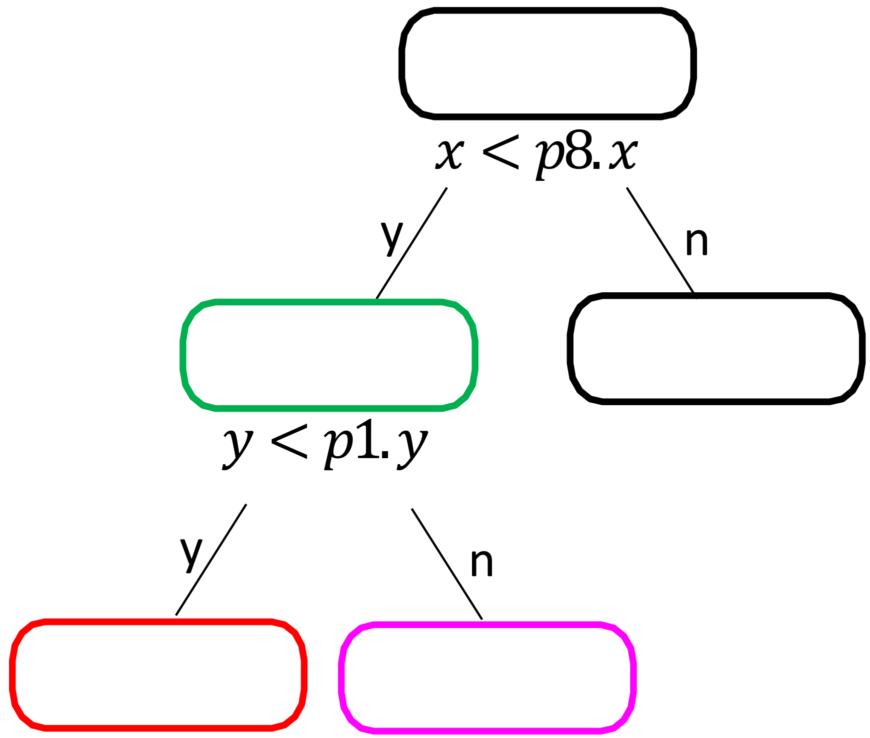

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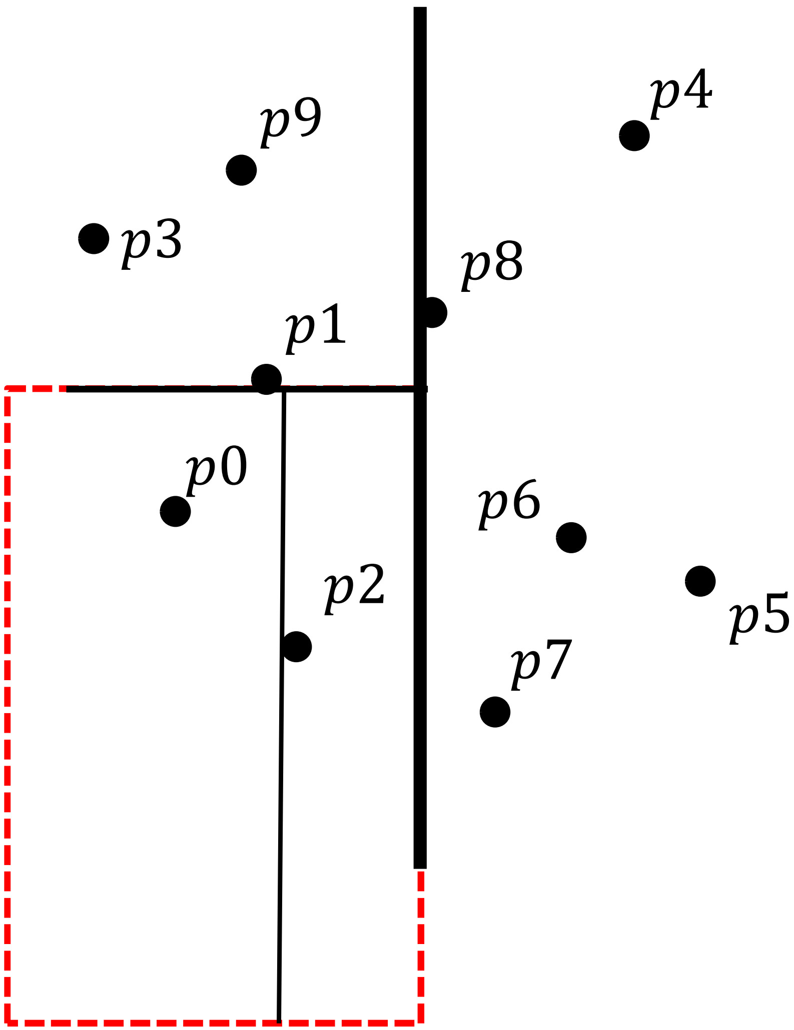

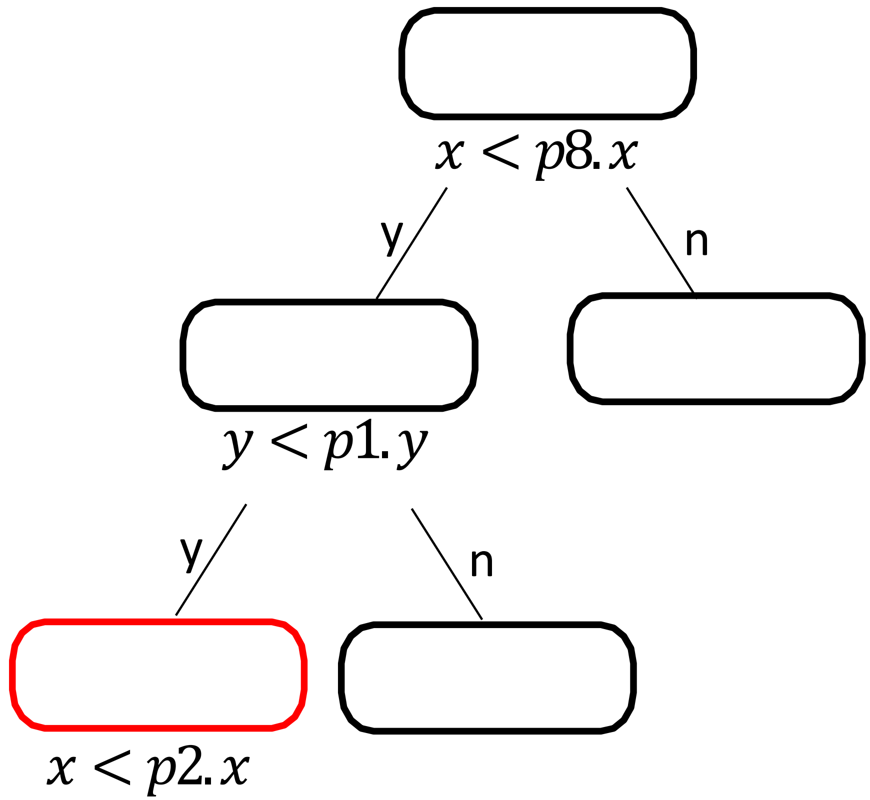

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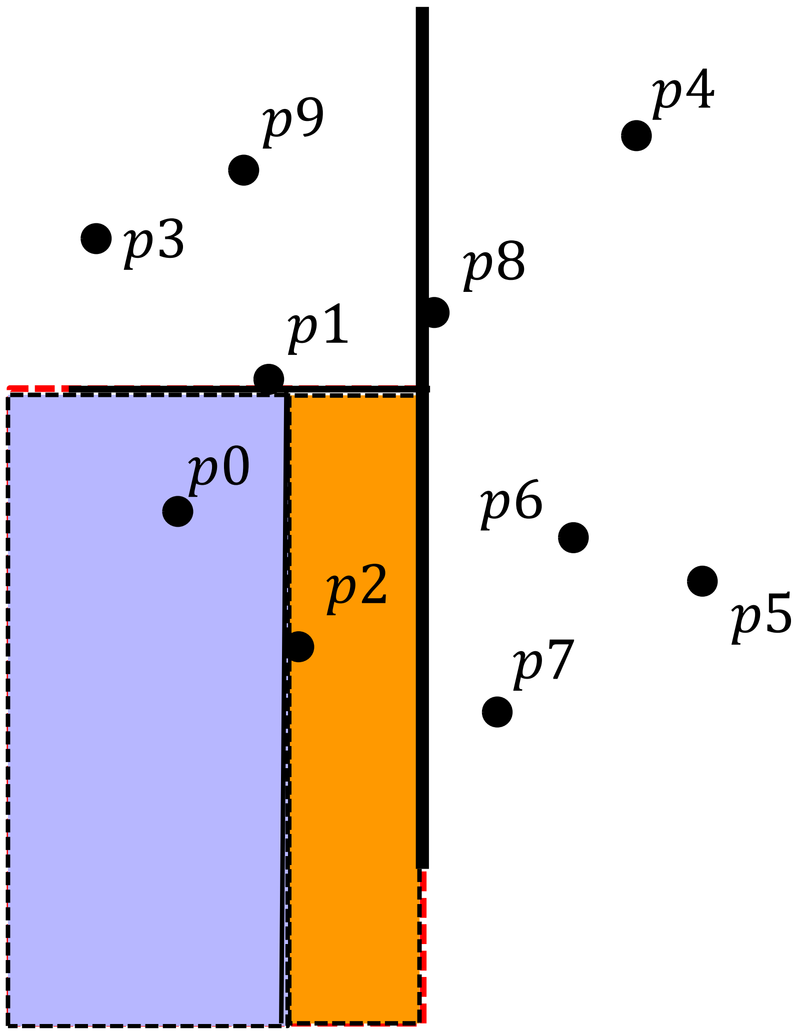

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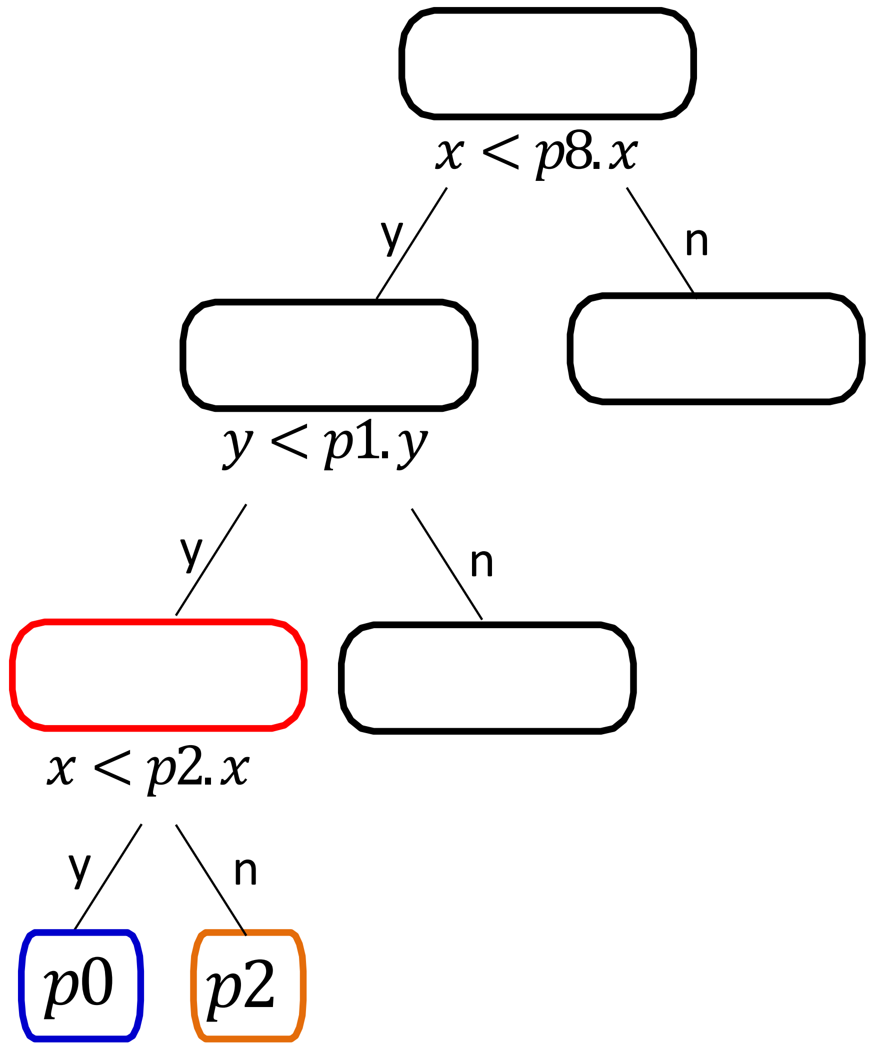

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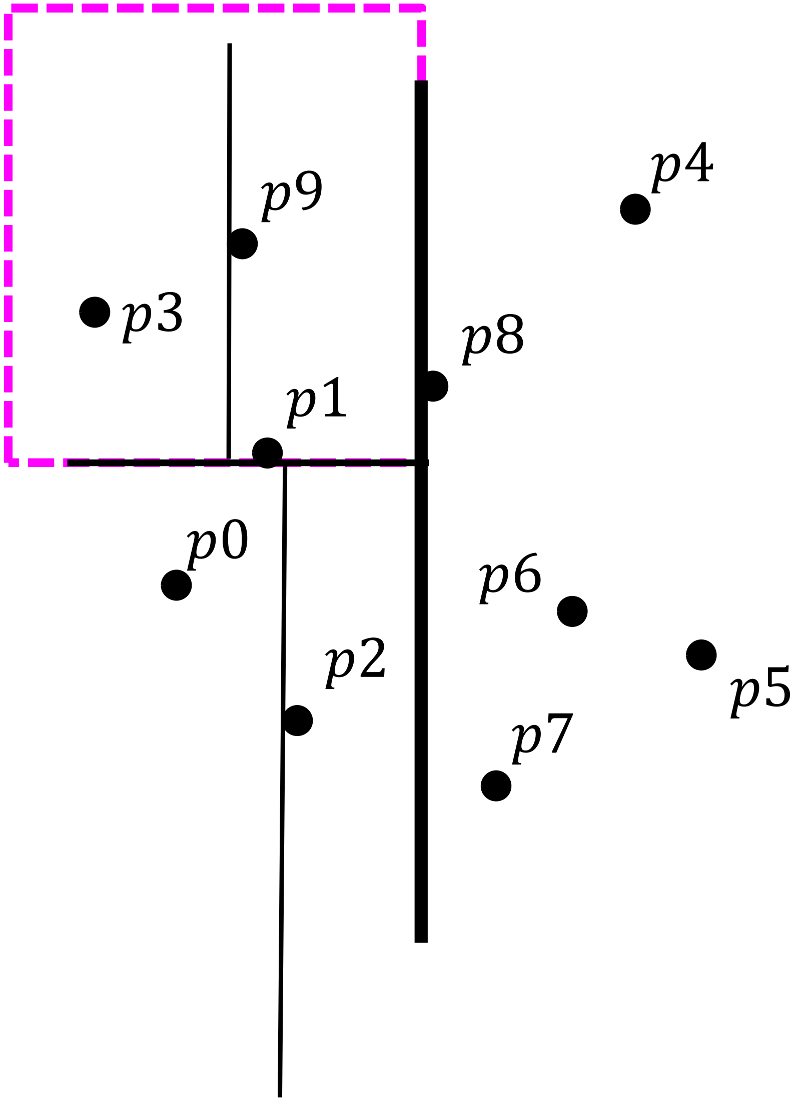

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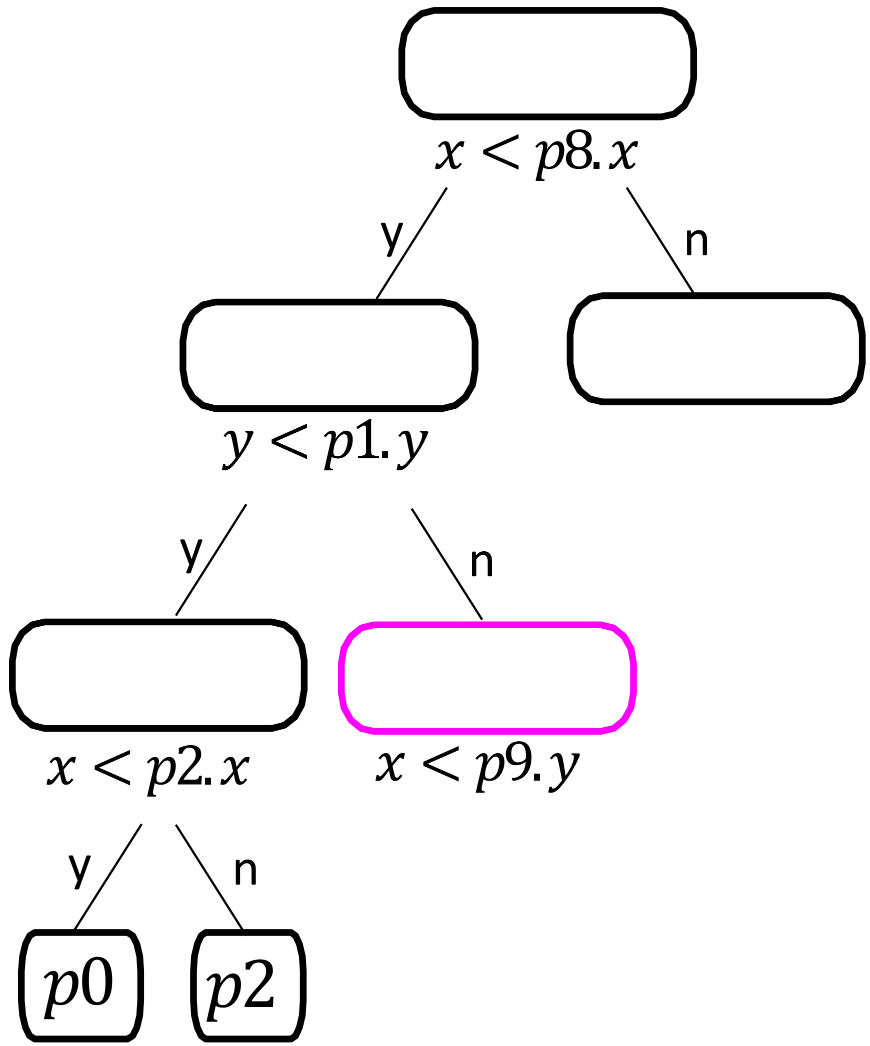

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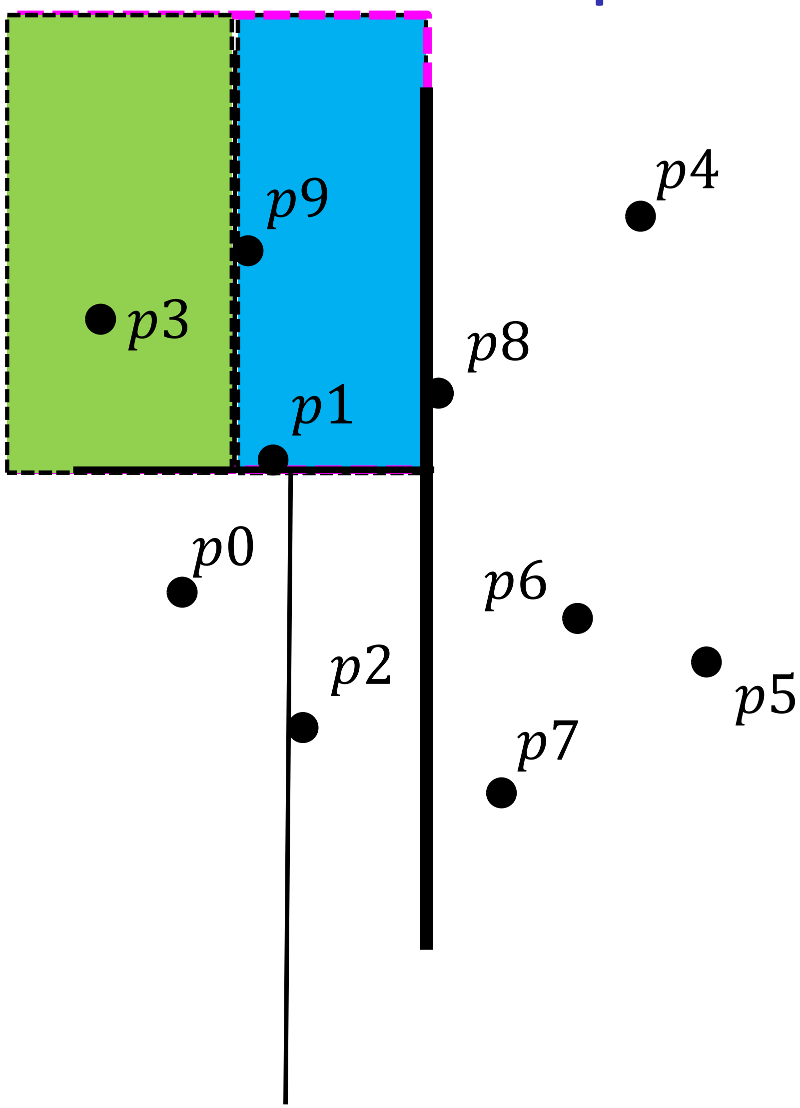

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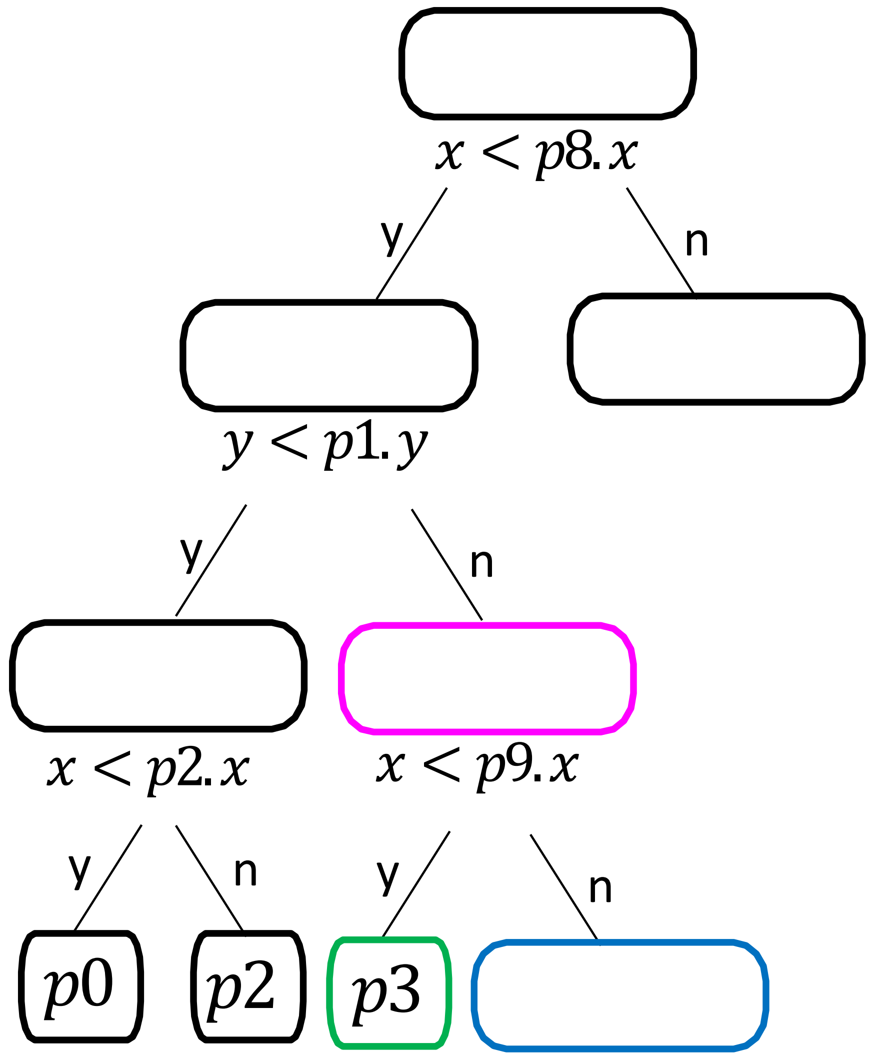

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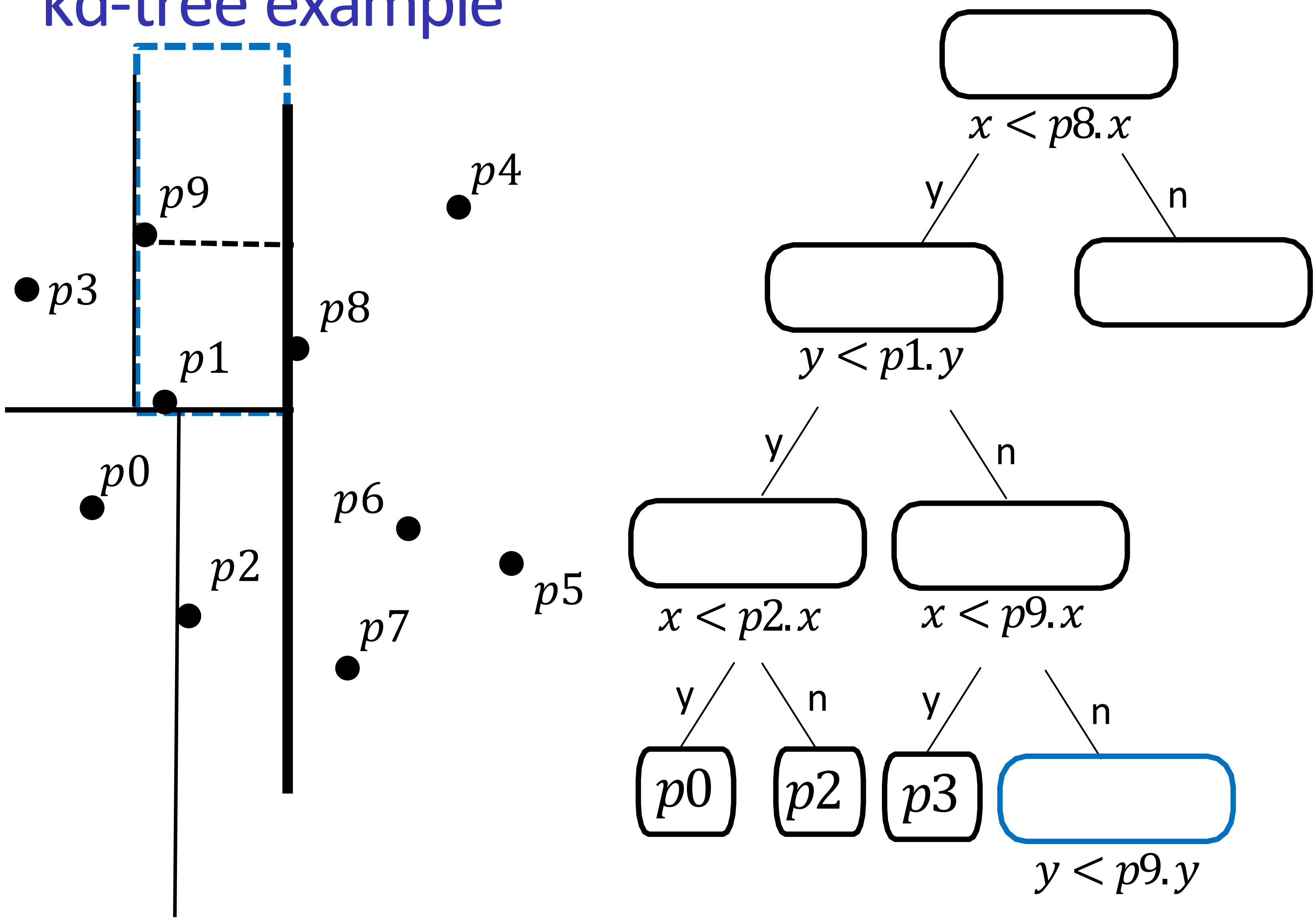

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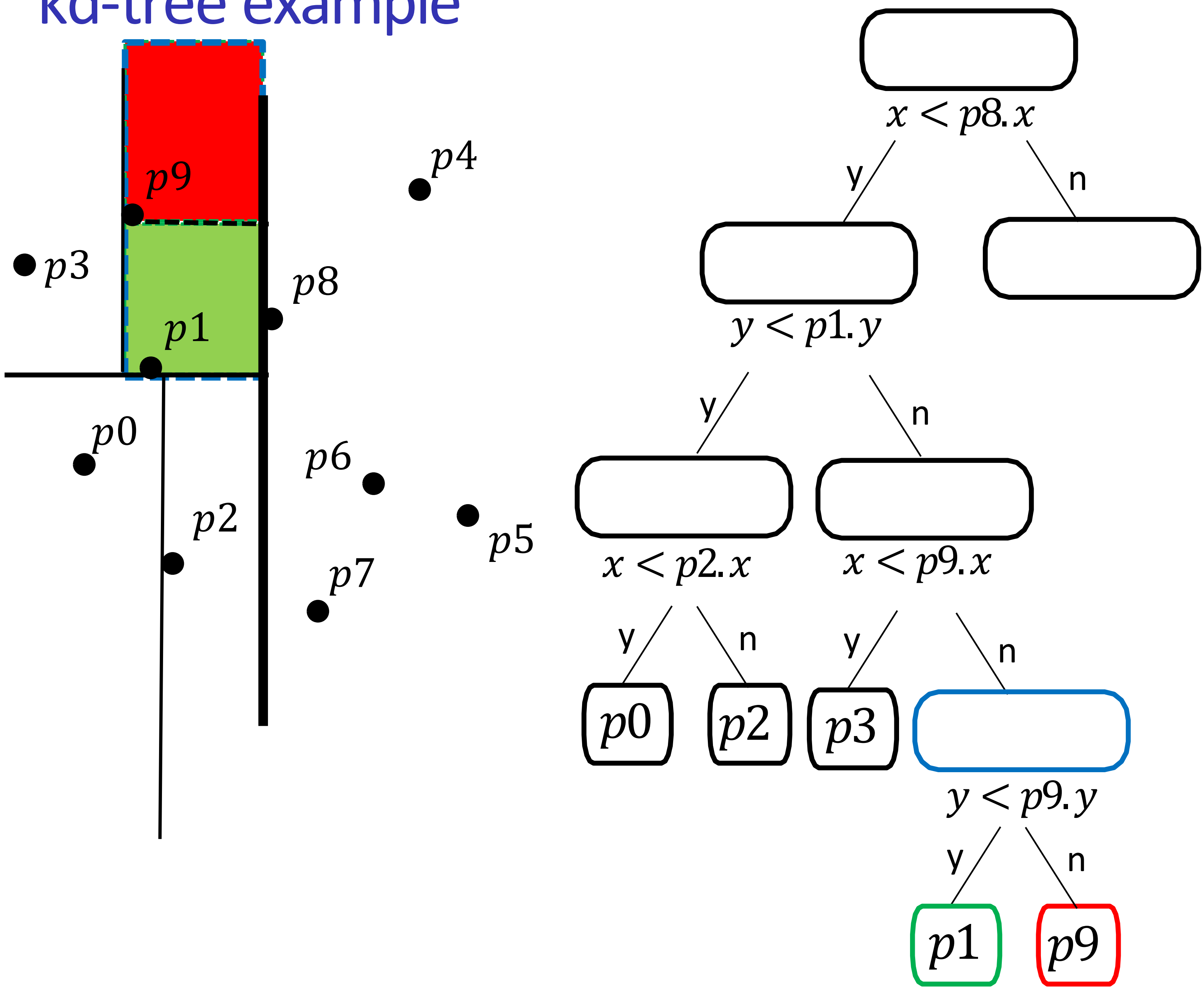

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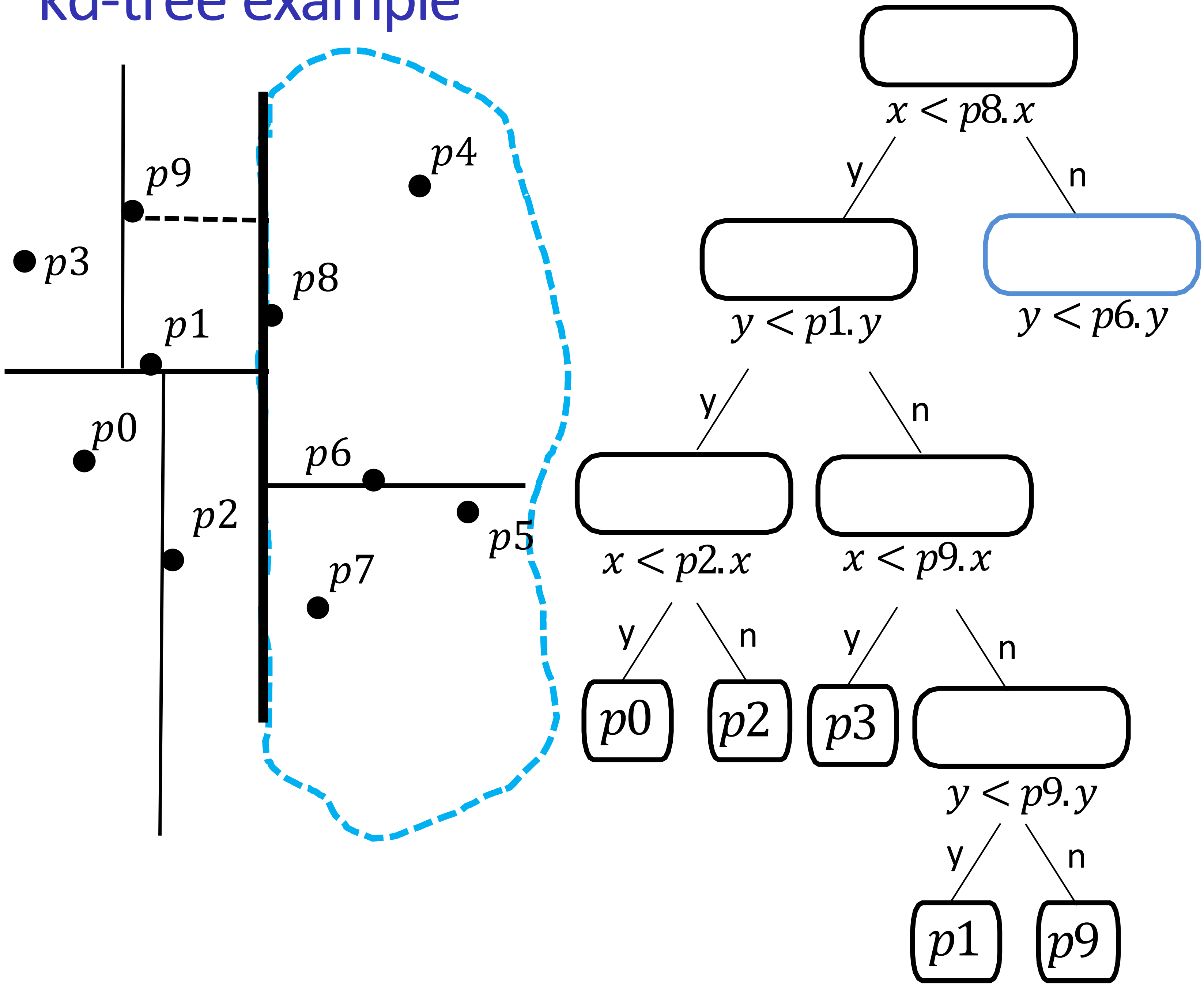

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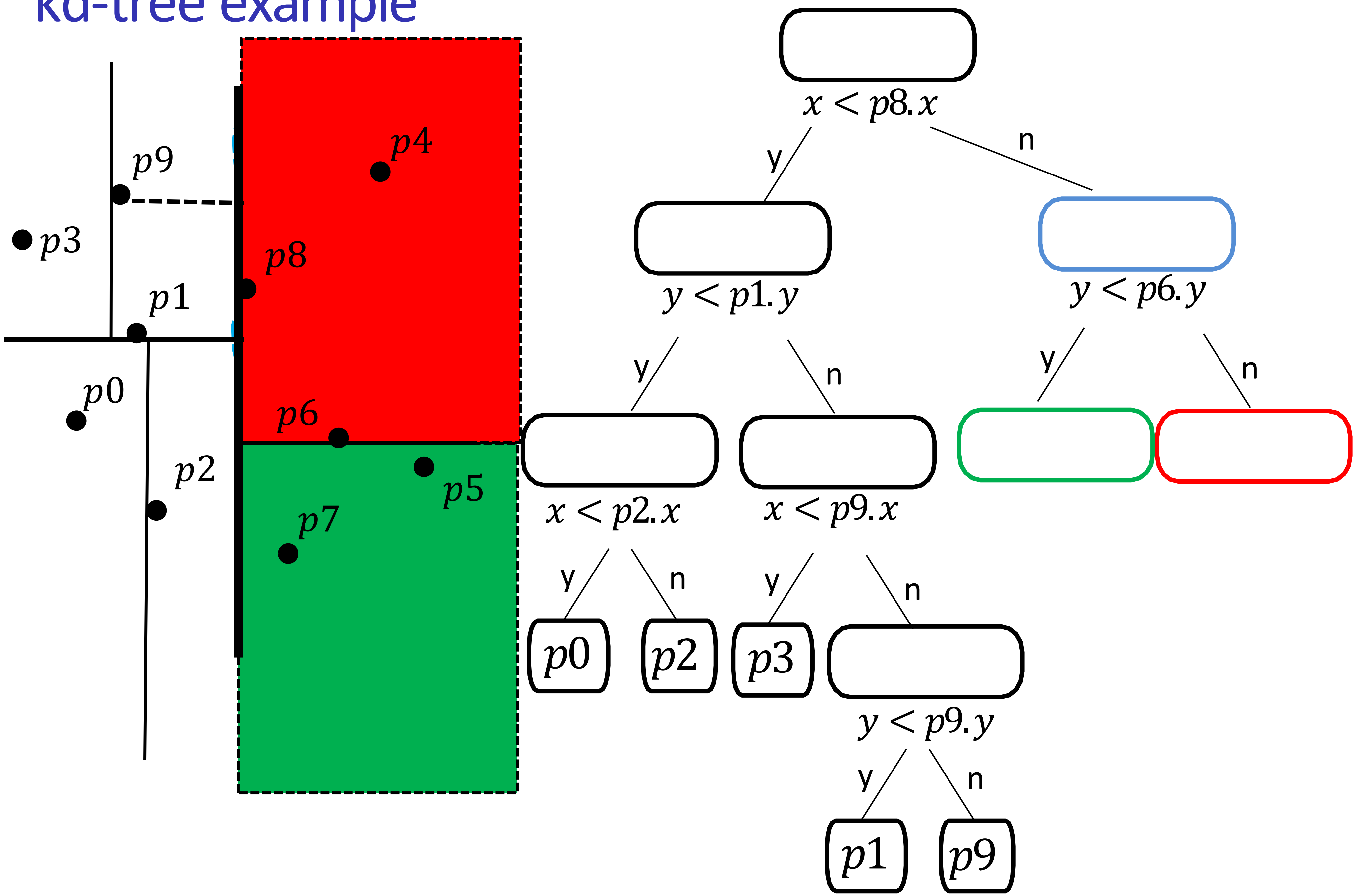

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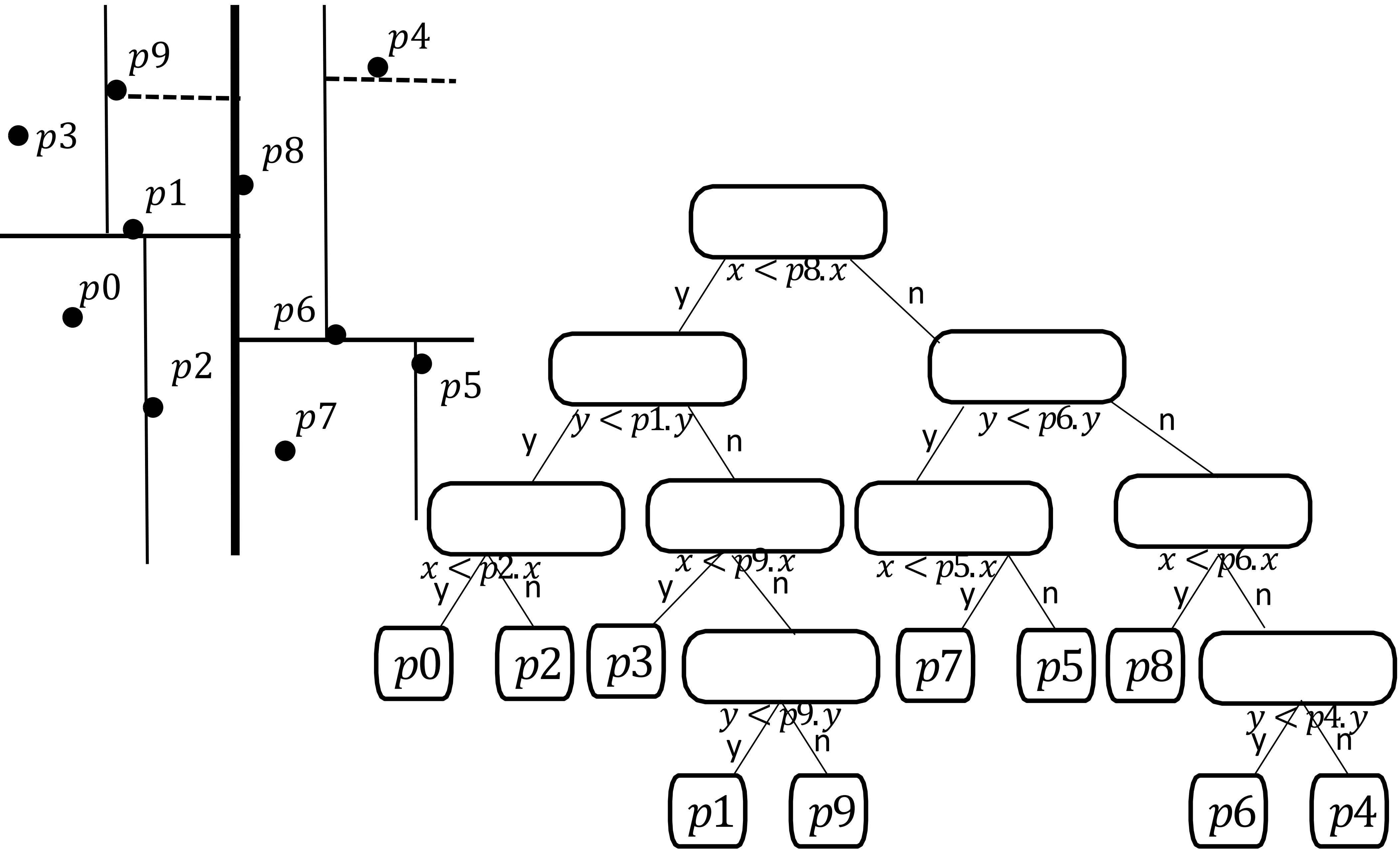

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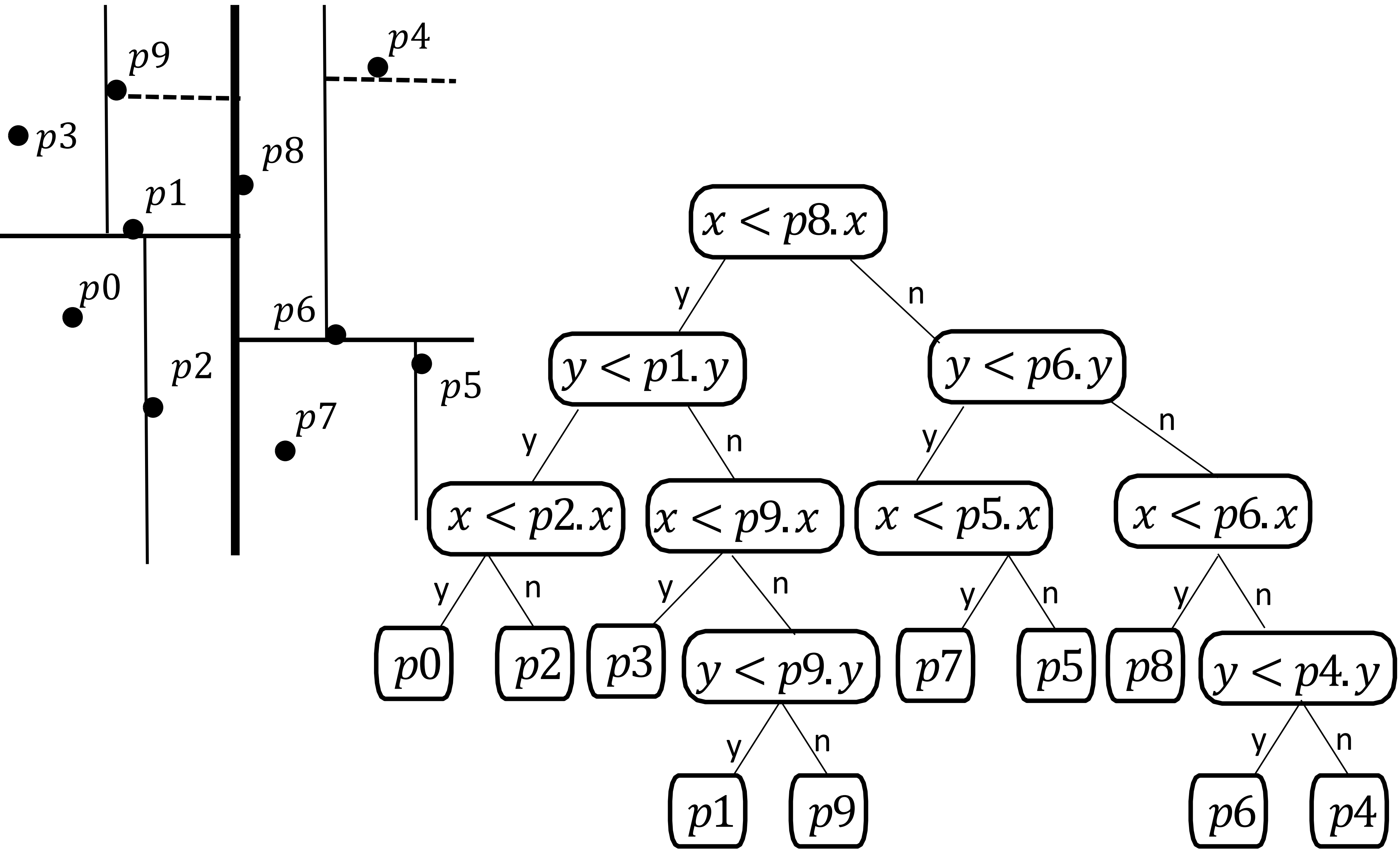


Building kd-trees

- Points $S = \{(x_0, y_0), (x_1, y_1), \ldots, (x_{n-1}, y_{n-1})\}$
- To build kd-tree with initial x-split
  - if $|S| \leq 1$ create a leaf and return
  - else find x-coordinate in position $m = \left\lfloor \frac{n}{2} \right\rfloor$ in sorted list of x -coordinates

    or partition by calling *quickSelect*$(S, \left\lfloor \frac{n}{2} \right\rfloor)$
    - partition S into $S_{x<m}$ and $S_{x \geq m}$ by comparing the x coordinate of a point with m
      - $\left\lfloor \frac{n}{2} \right\rfloor$ goes to one side and $\left\lceil \frac{n}{2} \right\rceil$ to the other
    - create left subtree recursively (splitting on y) for points $S_{x<m}$
    - create right subtree recursively (splitting on y) for points $S_{x \geq m}$
    - each node keeps track of the splitting line
- Building with initial y-split symmetric
- Points on split lines belong to right/top side

kd-tree Construction Running Time and Space

- Partition S in $\Theta(n)$ expected time with *QuickSelect*
- Both subtrees have $\approx n/2$ points
- Sloppy recurrence
  - $T^{exp}(n) = 2T^{exp}\left(\frac{n}{2}\right) + O(n)$
  - resolves to $\Theta(n \log n)$ expected time
- Can improve to $\Theta(n \log n)$ worst-case runtime by pre-sorting coordinates
- Recurrence inequality for height

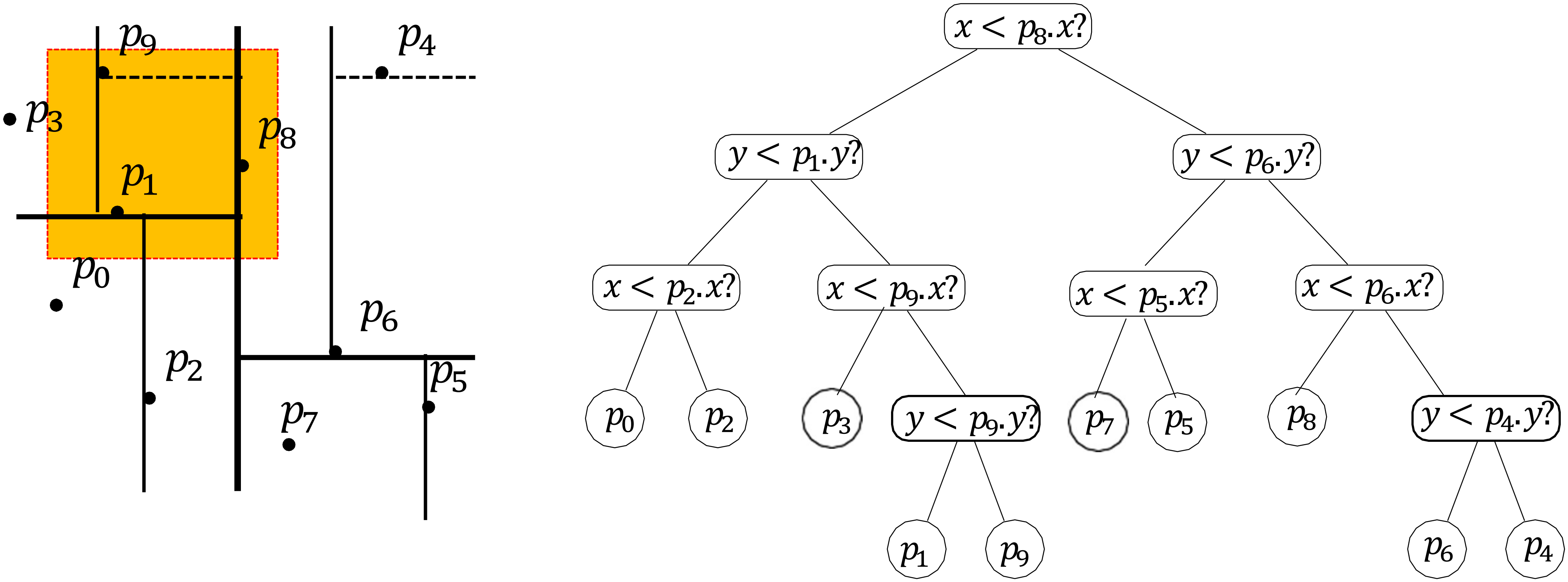
$$h(1) = 0$$
$$h(n) \leq h\left(\left\lceil\frac{n}{2}\right\rceil\right) + 1$$

  - resolves to $O(\log n)$, specifically $\lceil \log n \rceil$
  - this is tight (binary tree with n leaves)
- Space
  - all interior nodes have exactly 2 children, therefore $n - 1$ interior nodes
  - total number of nodes is $2n - 1$
  - space is $\Theta(n)$

kd-tree Dictionary Operations

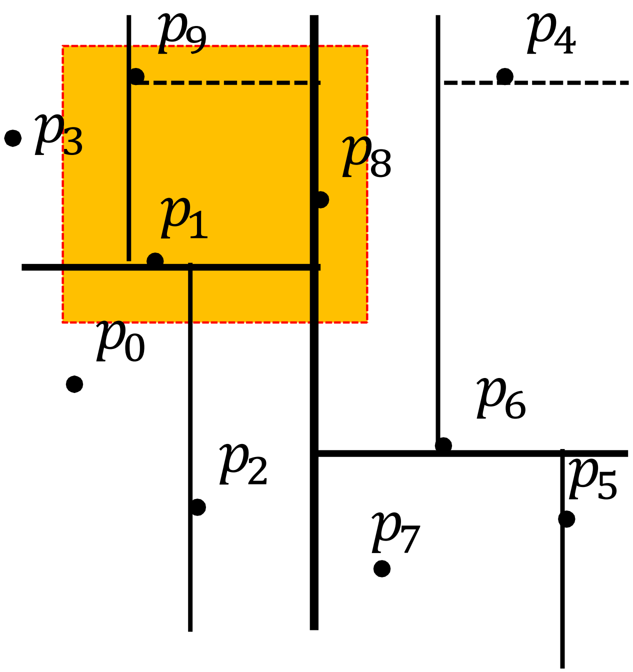
- *search* as in binary search tree using indicated coordinate
- *insert* first search, insert as new leaf
- *delete* first search, remove leaf and any parent with one child
- **Problem**
    - after insert or delete, split might no longer be at exact median
    - height is no longer guaranteed to be $O(\log n)$
    - kd-tree do not handle insertion/delection well
    - remedy
        - allow a certain imbalance
        - re-building the entire tree when it becomes too unbalanced
        - no details
        - but *rangeSearch* will be slower

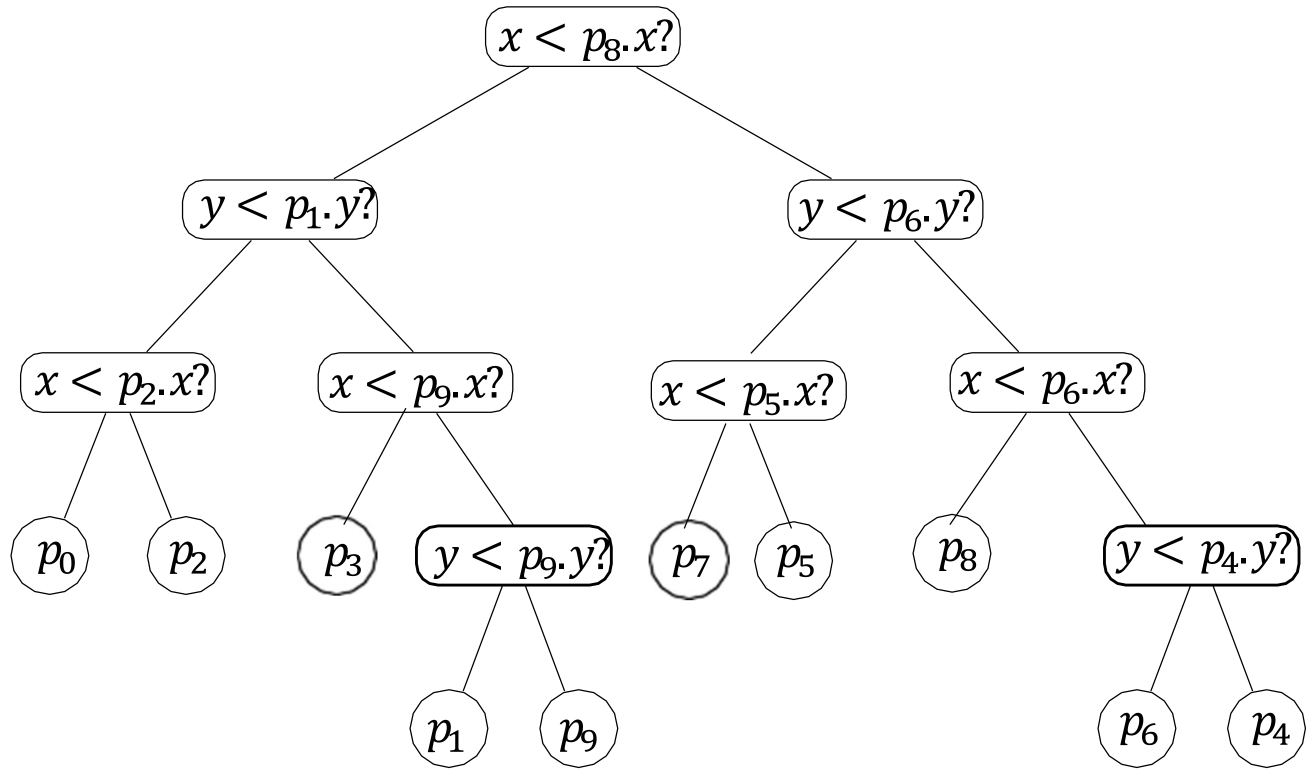
kd-tree: Range Search Example



- Every node is associated with a region
    - range search is exactly as for quadtrees, except there are only two children and leaves always store points

kd-tree: Range Search Example





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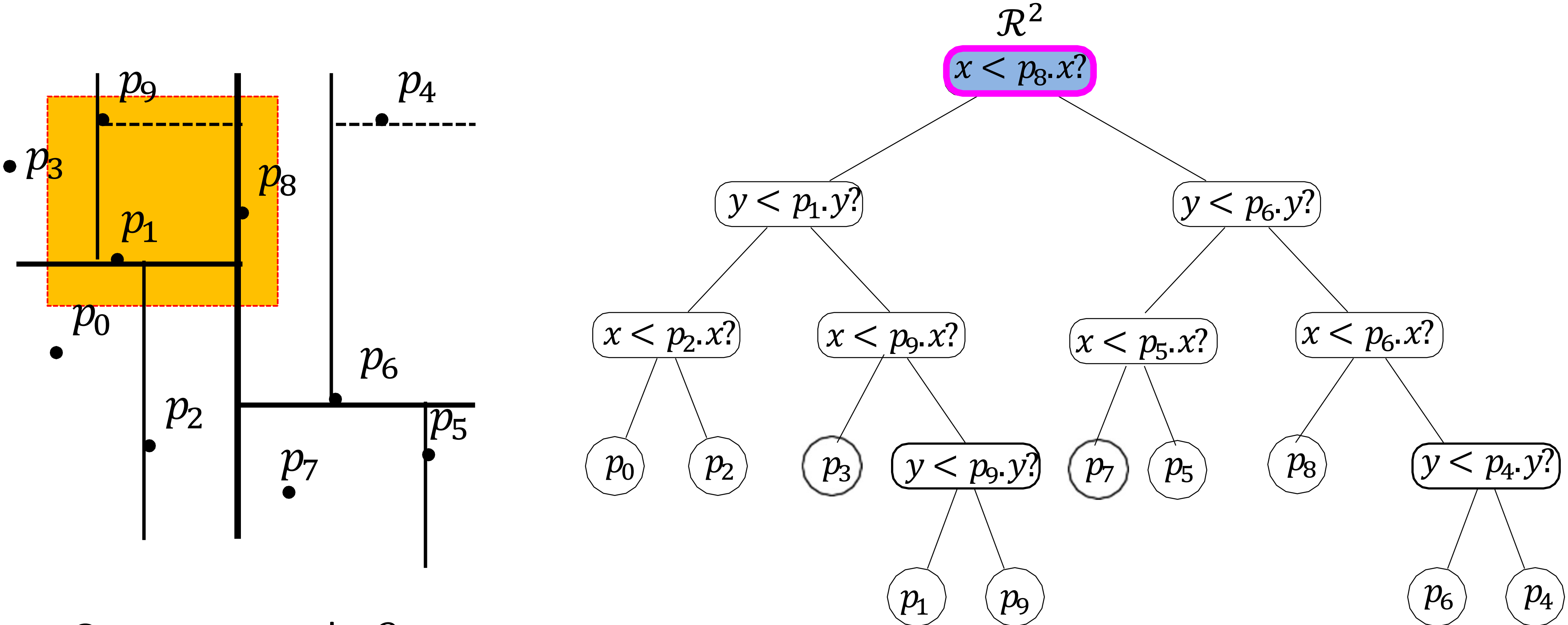

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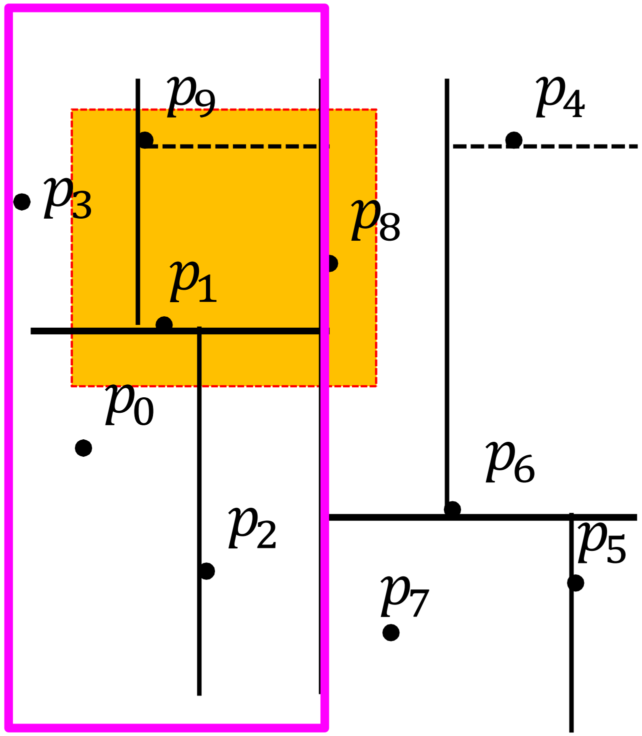

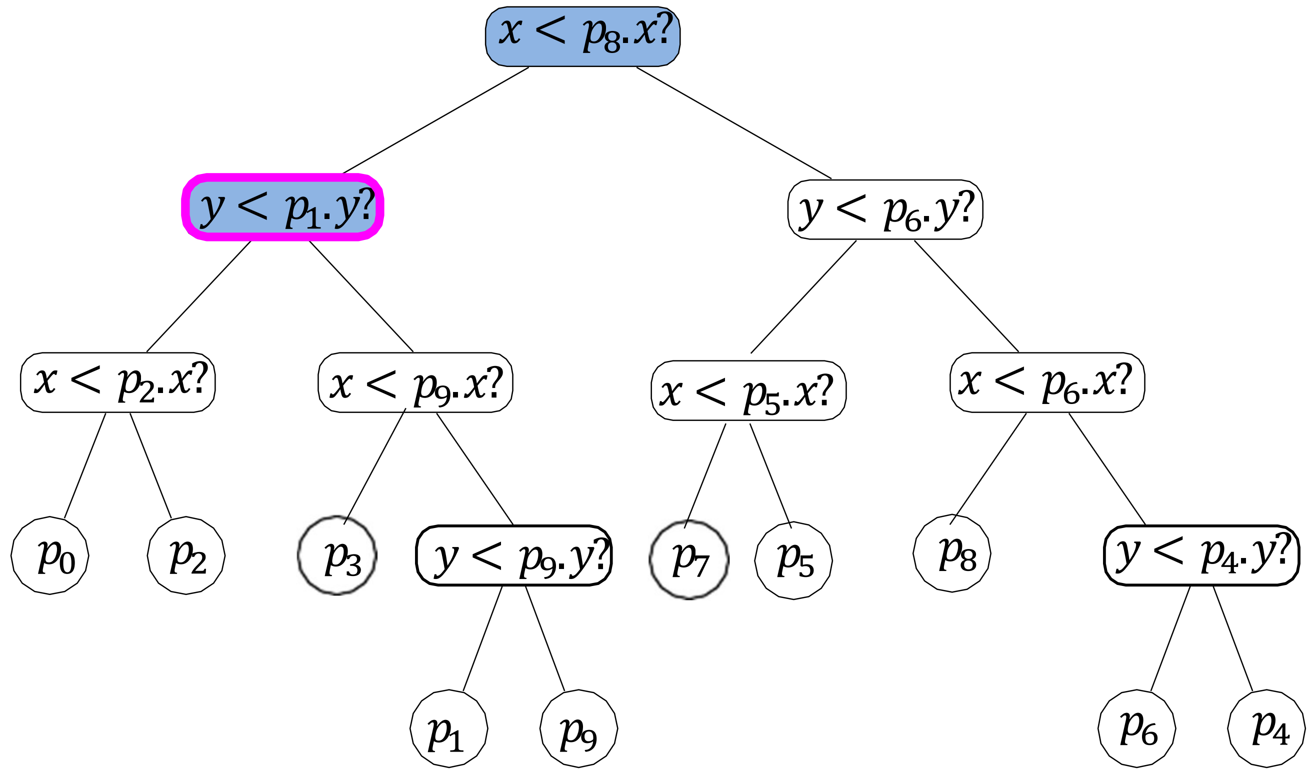

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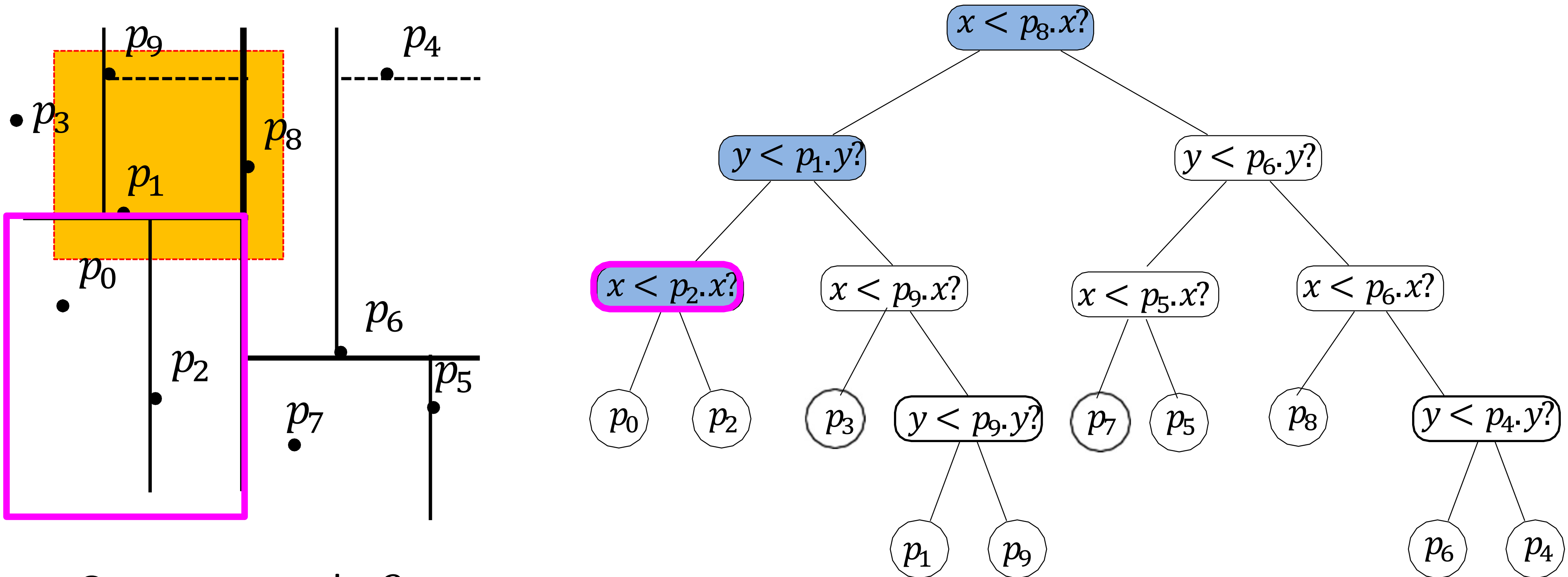

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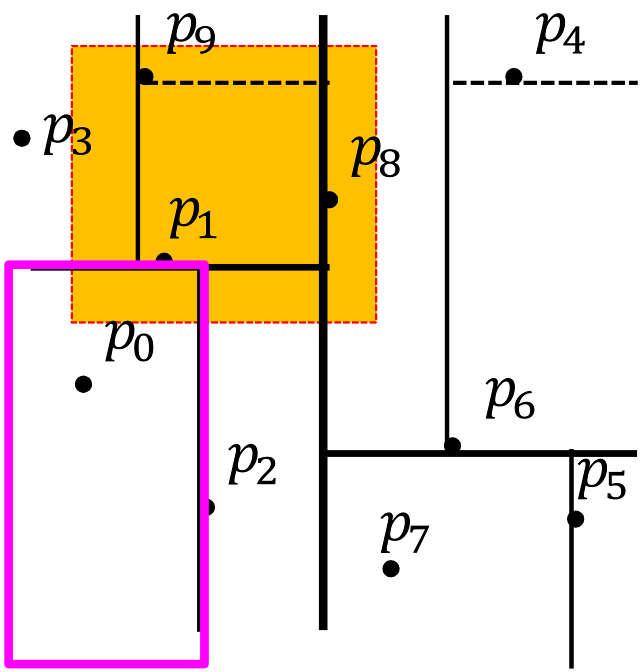

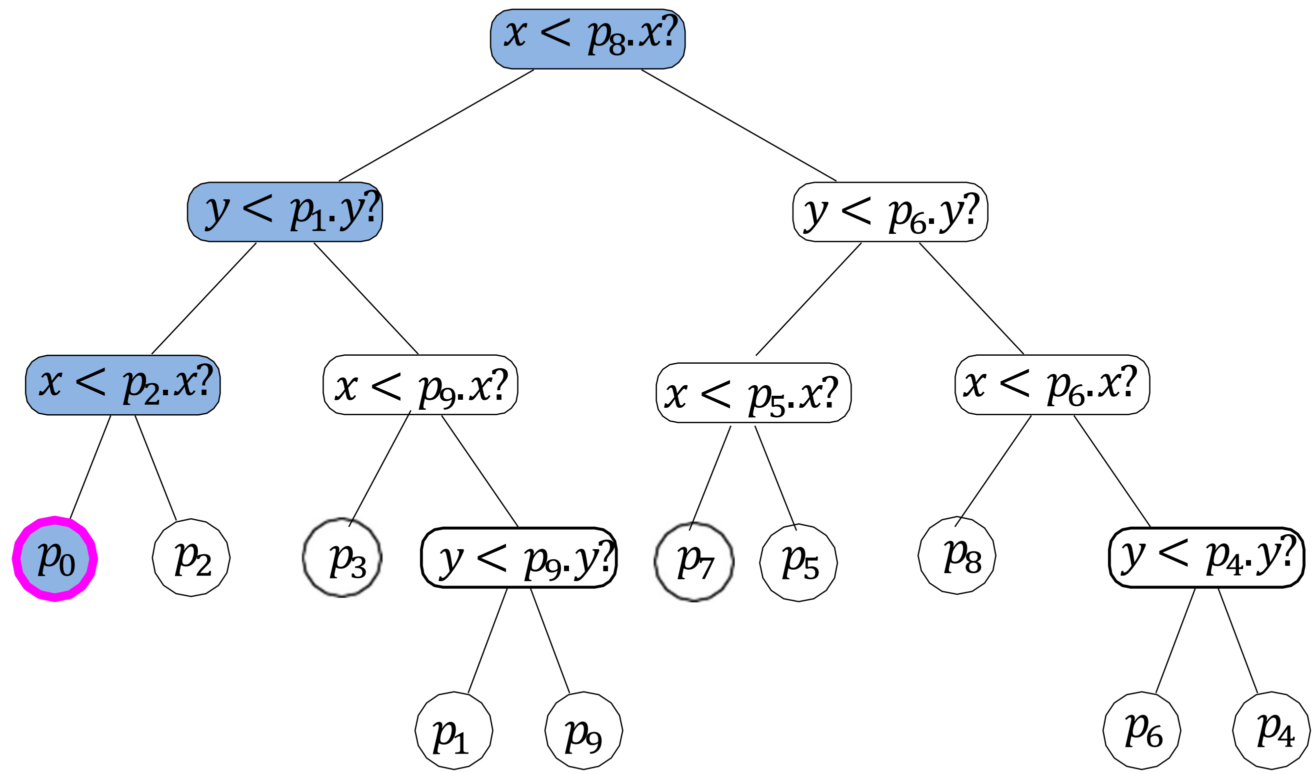

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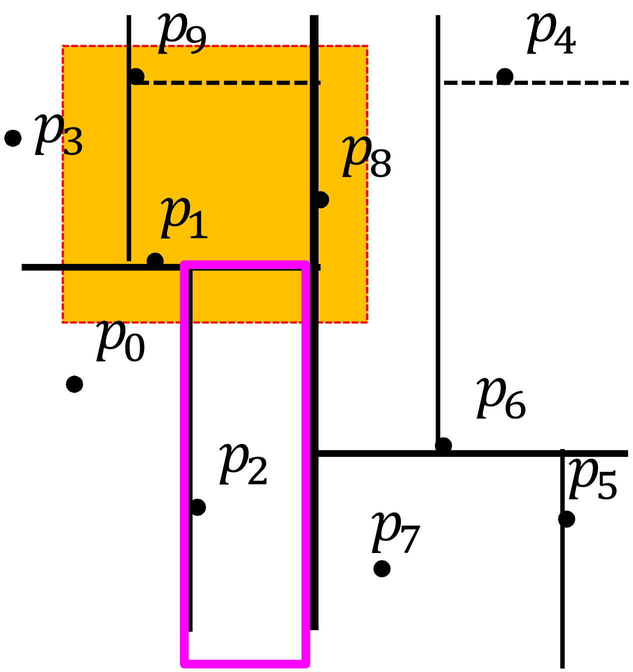

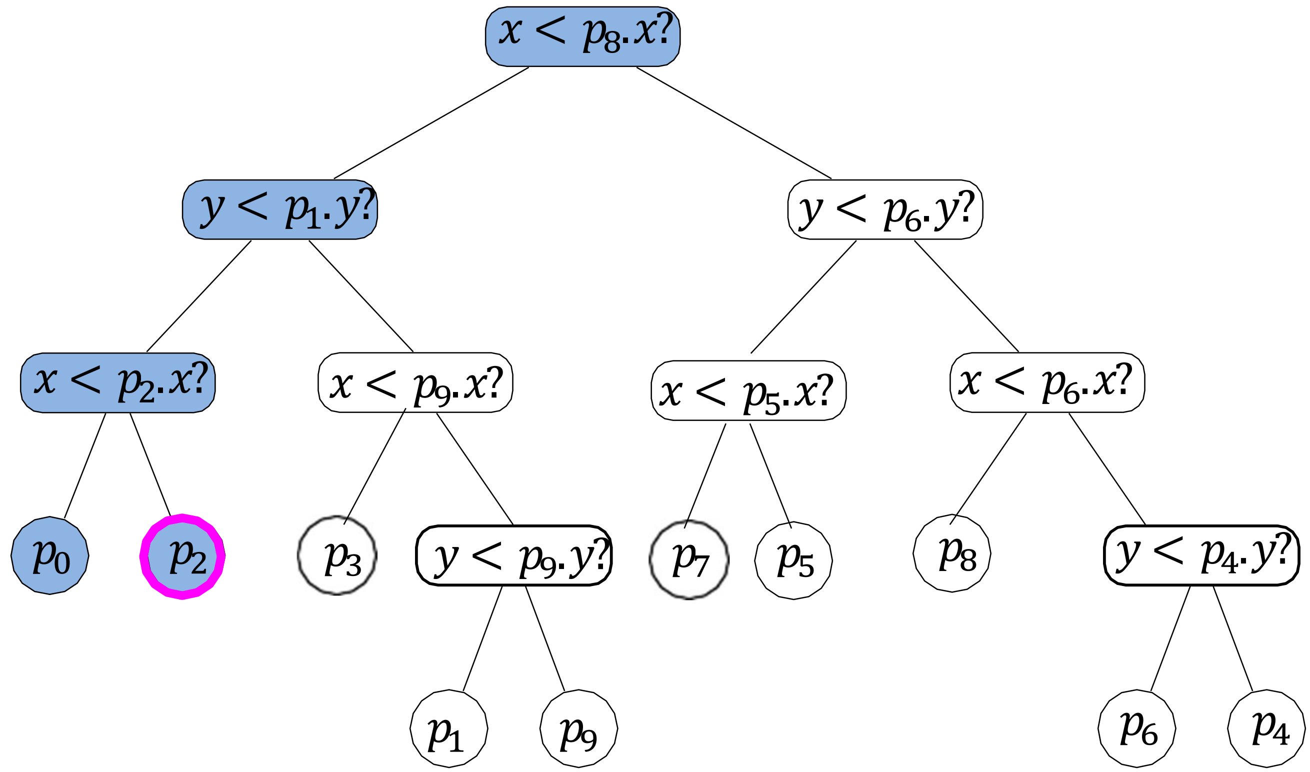

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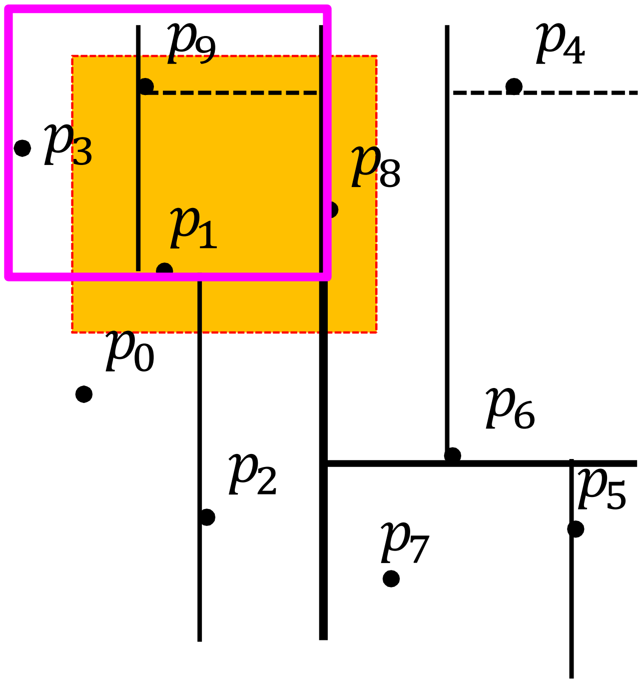

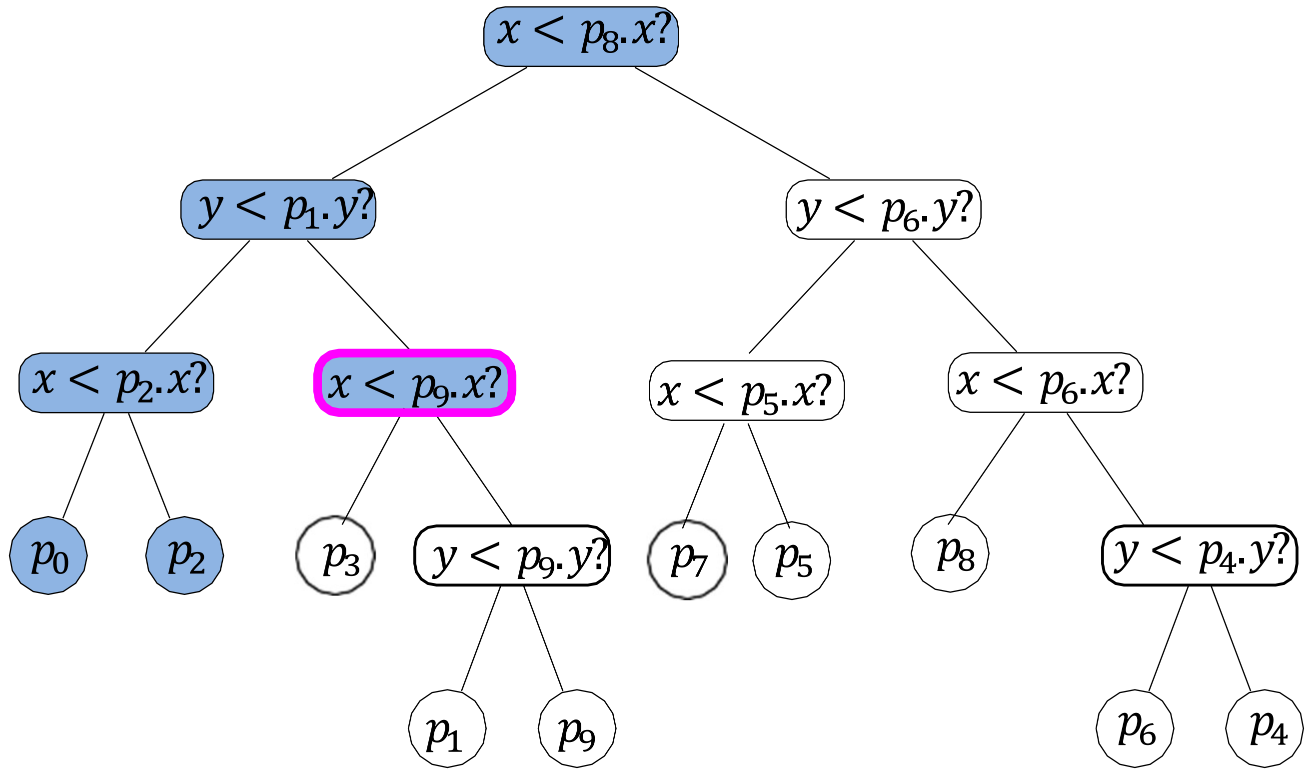

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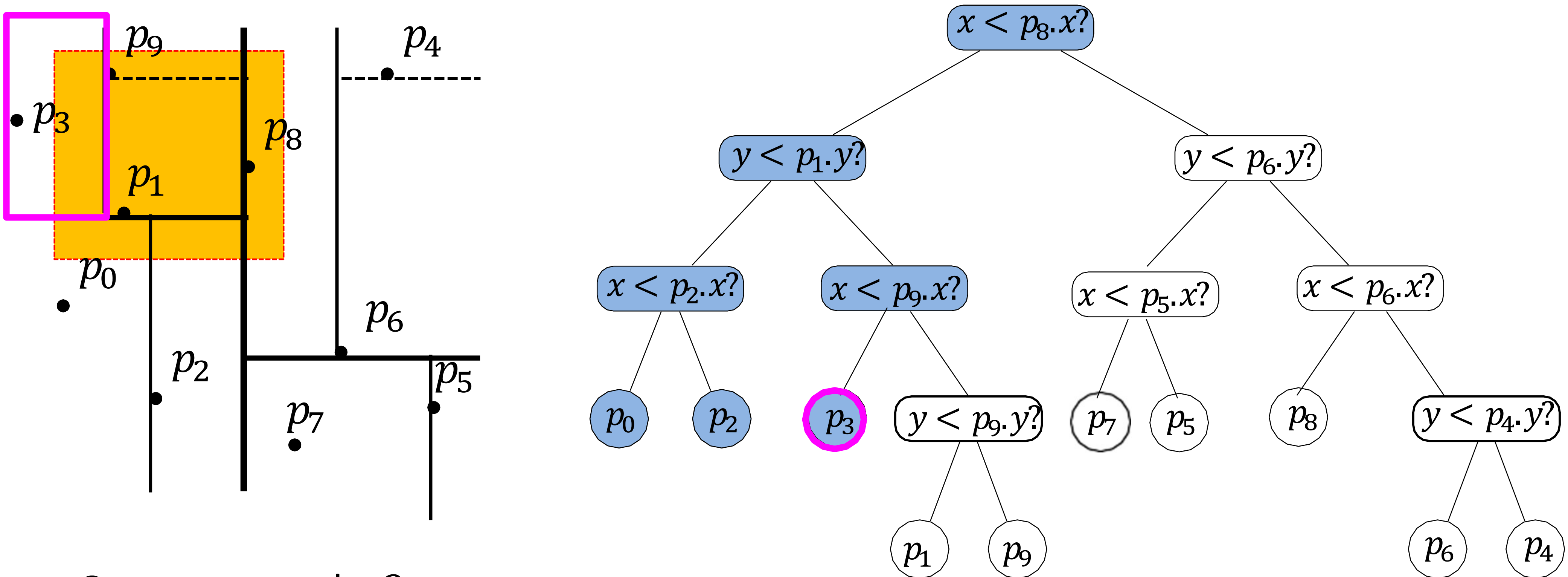

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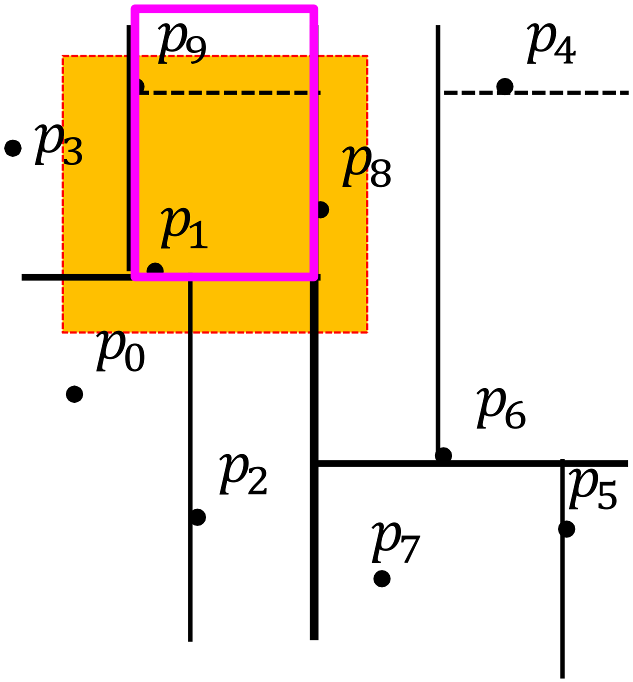

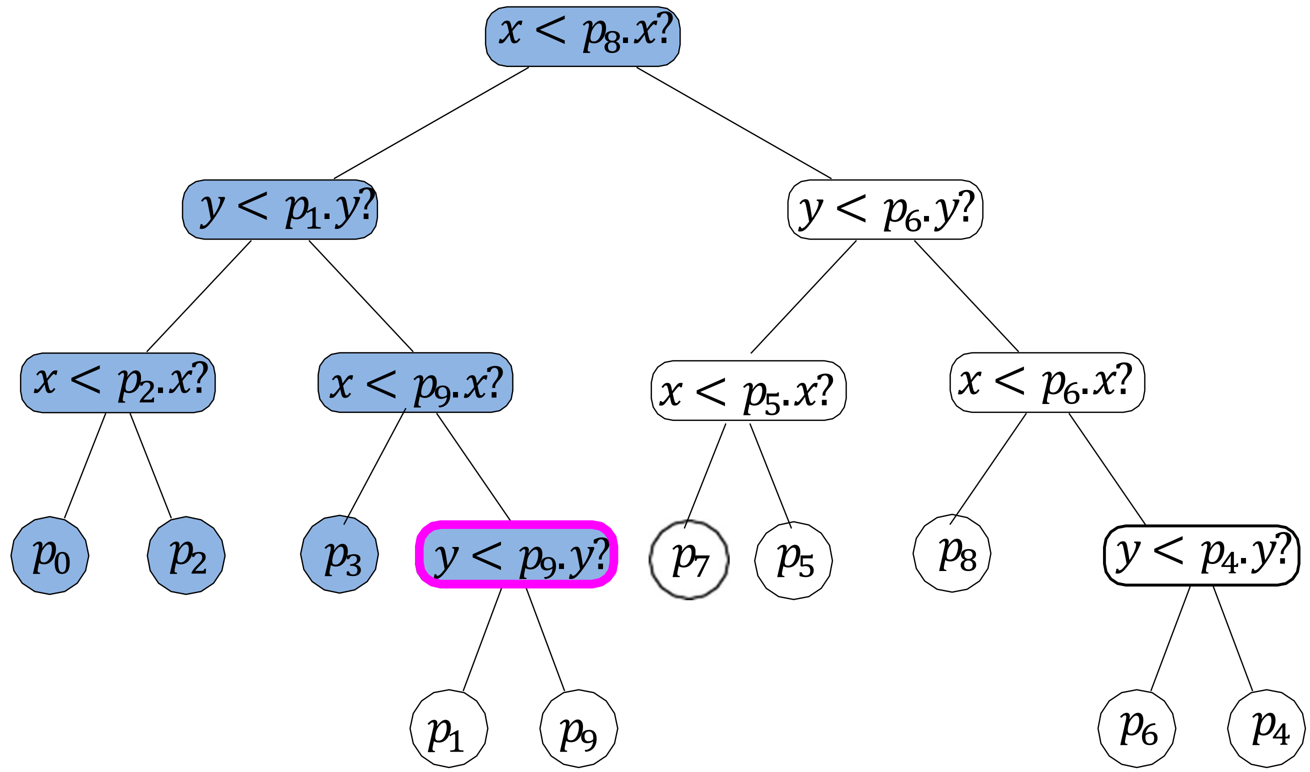

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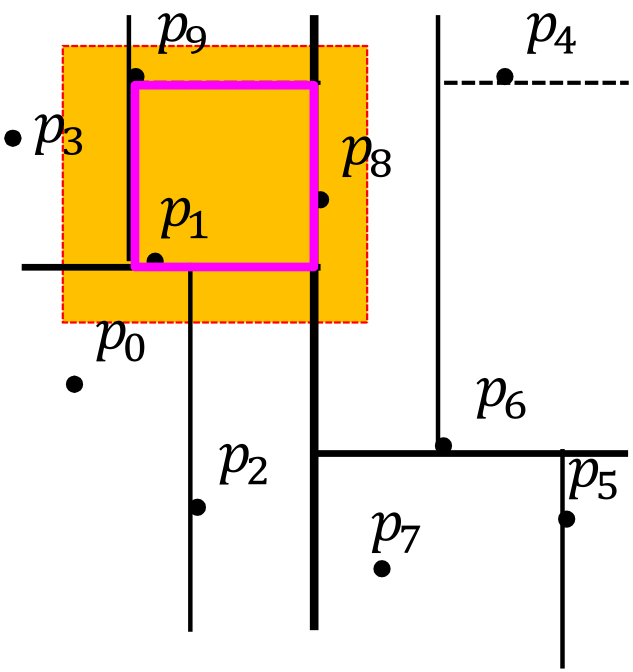

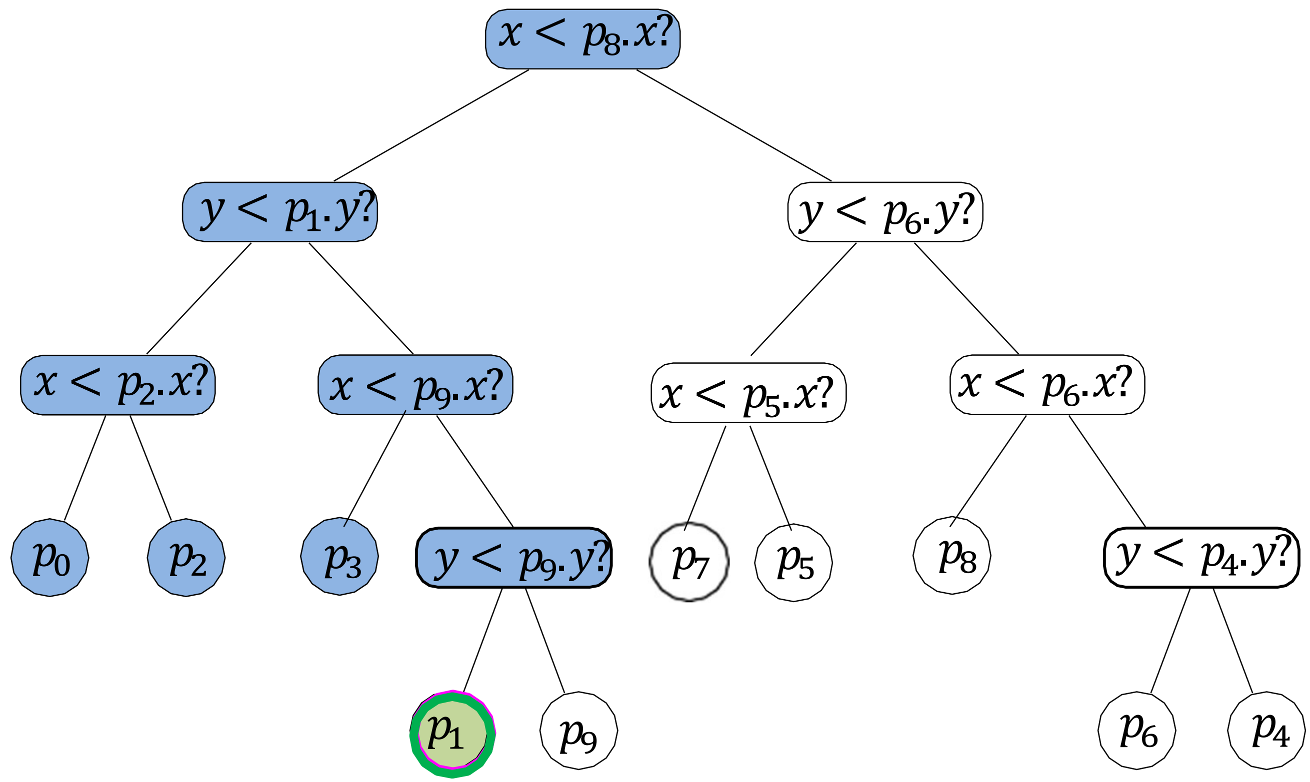

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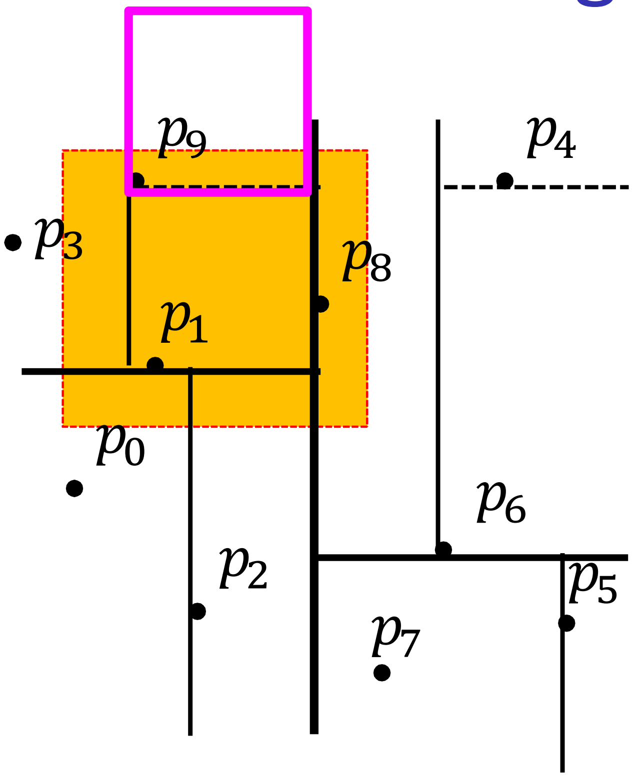

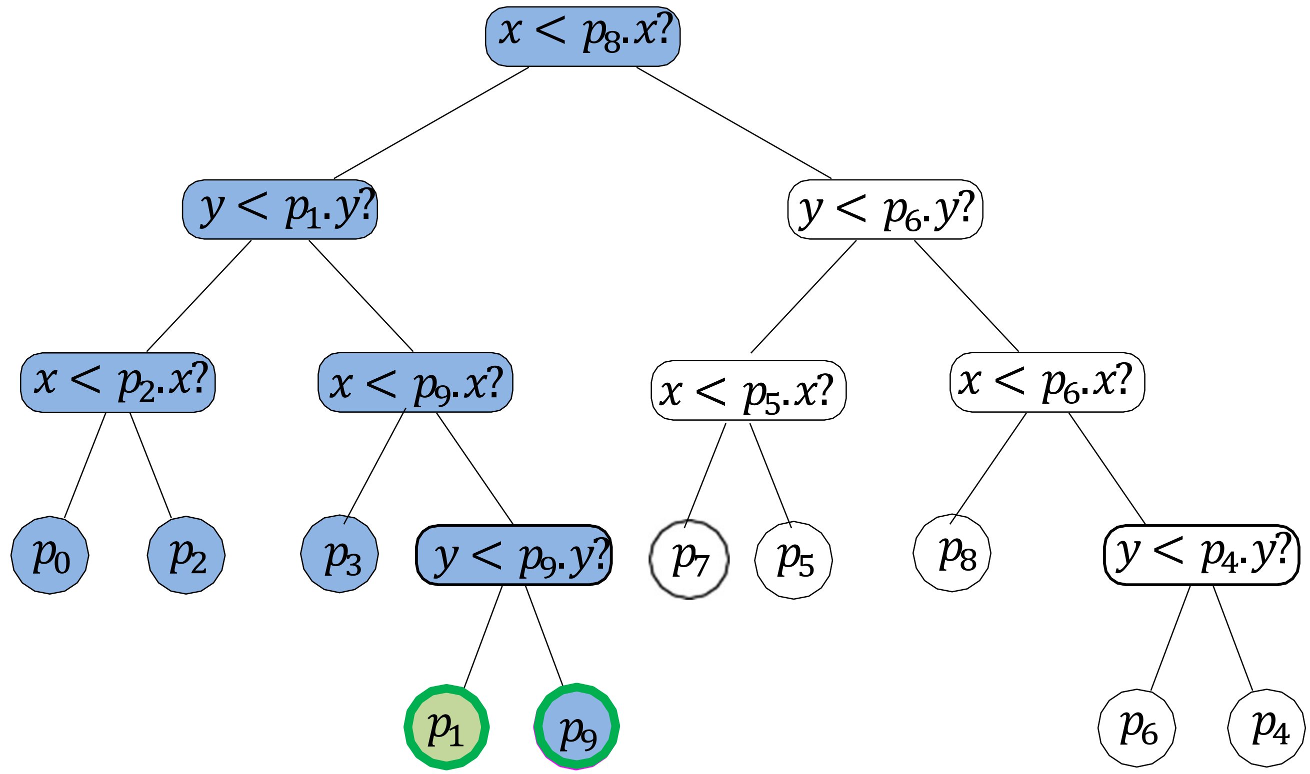

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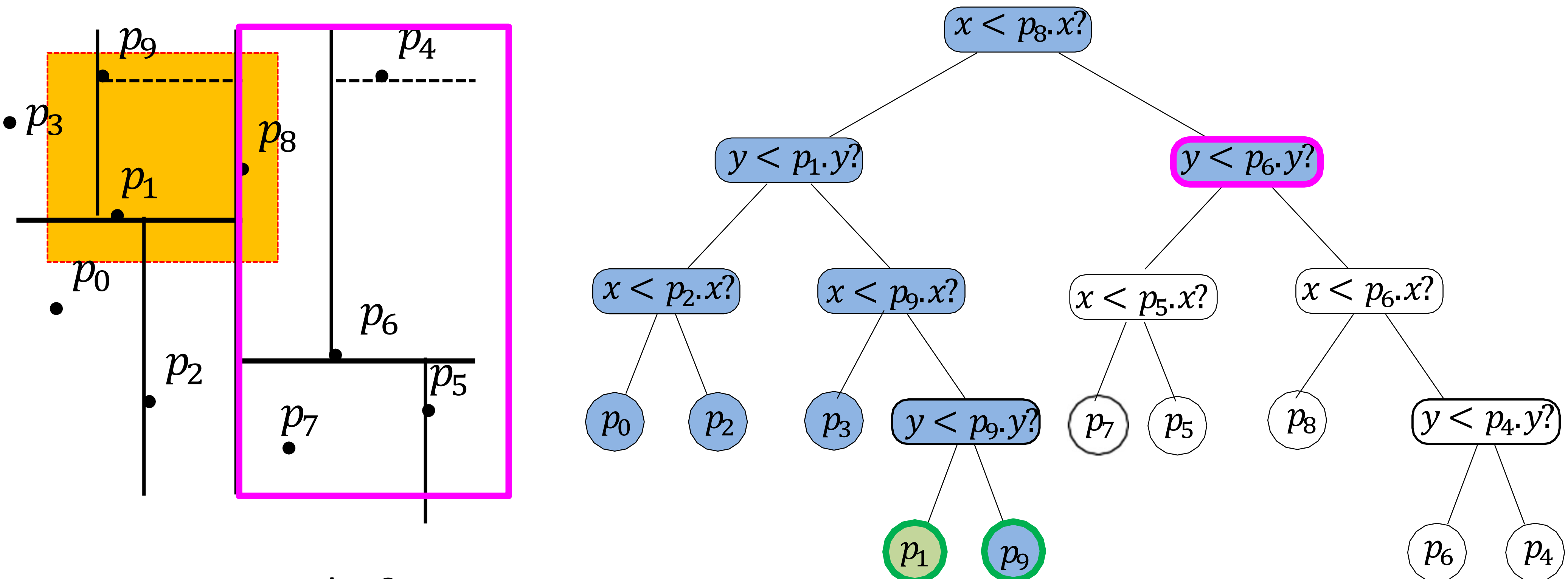

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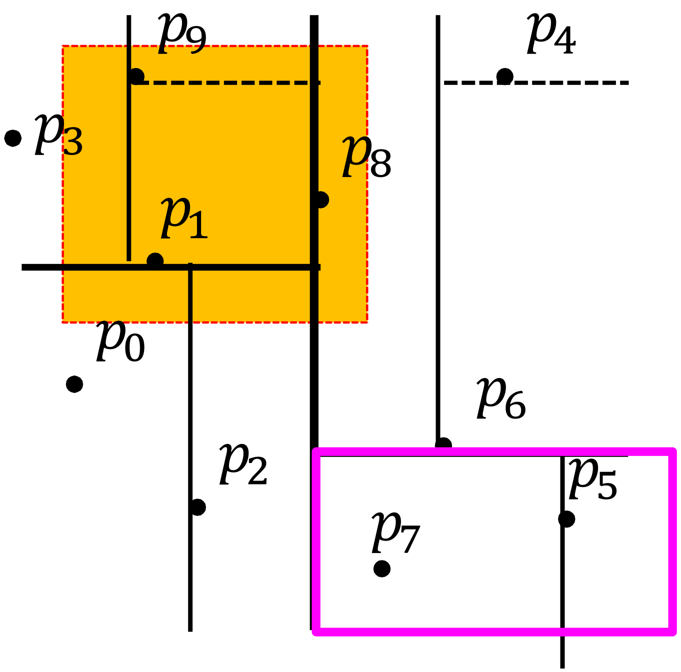

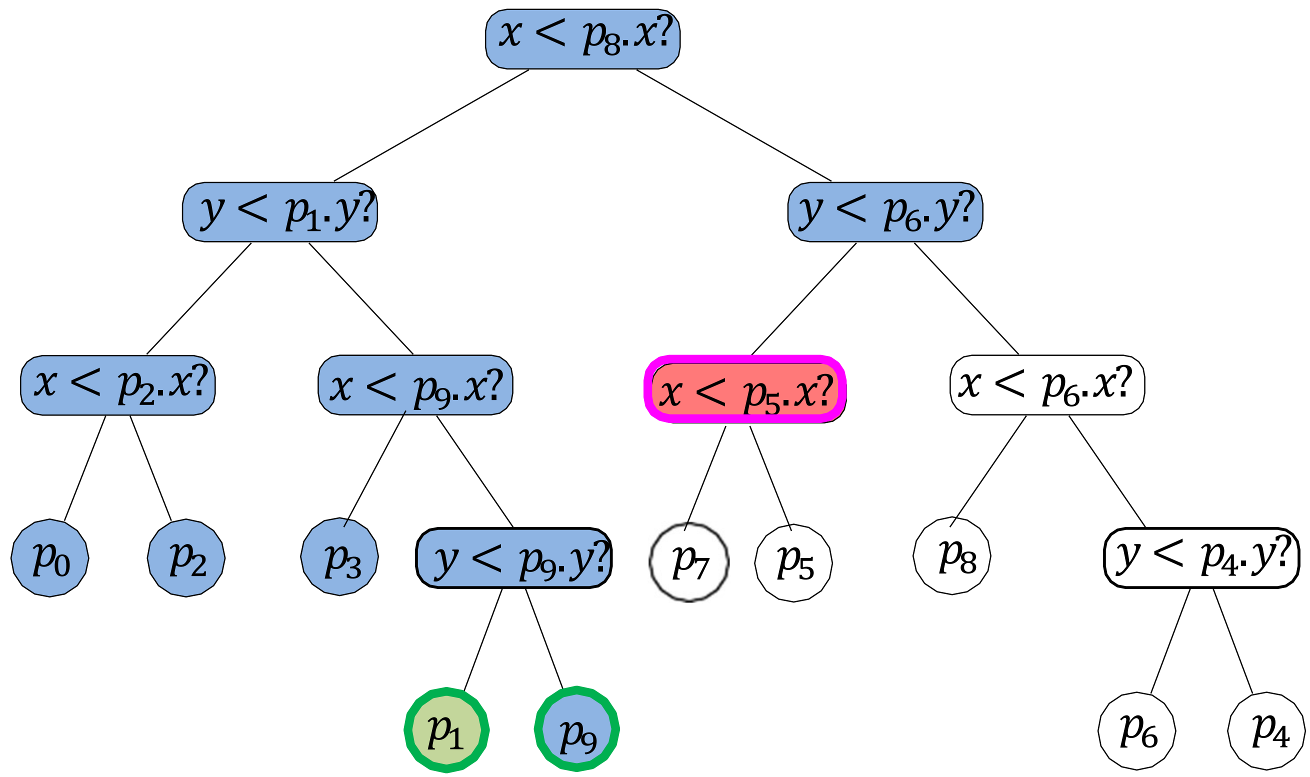

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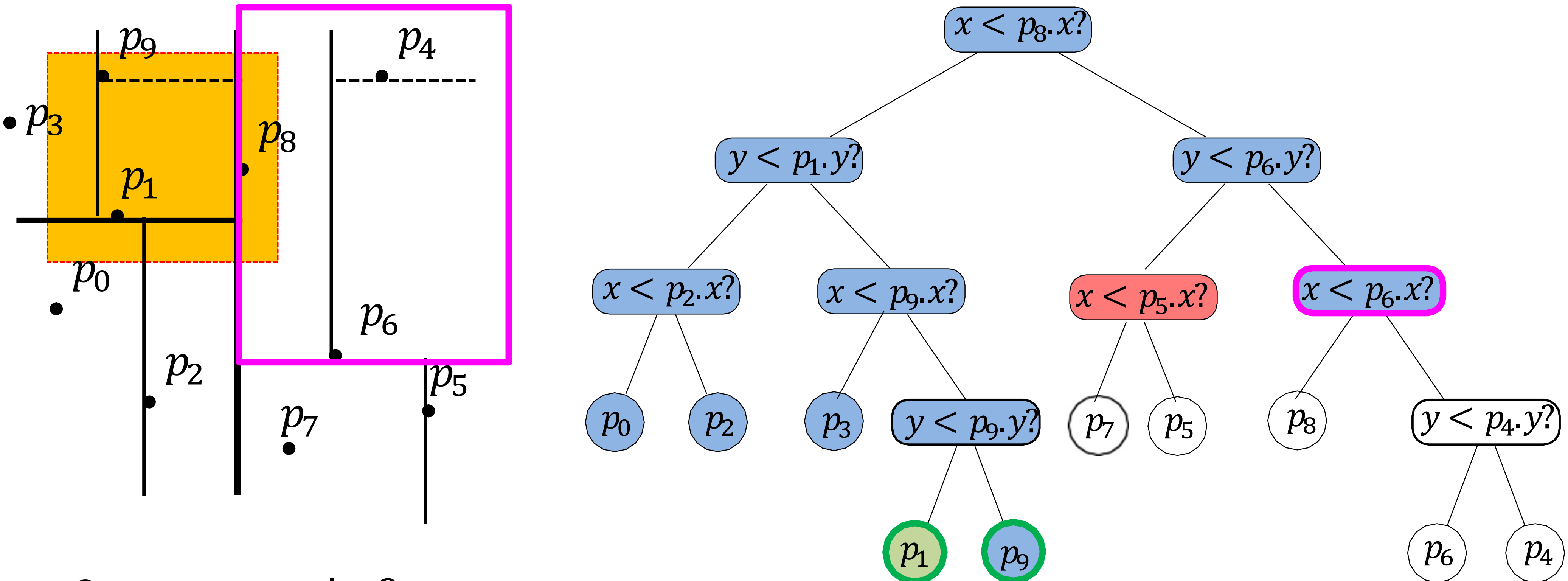

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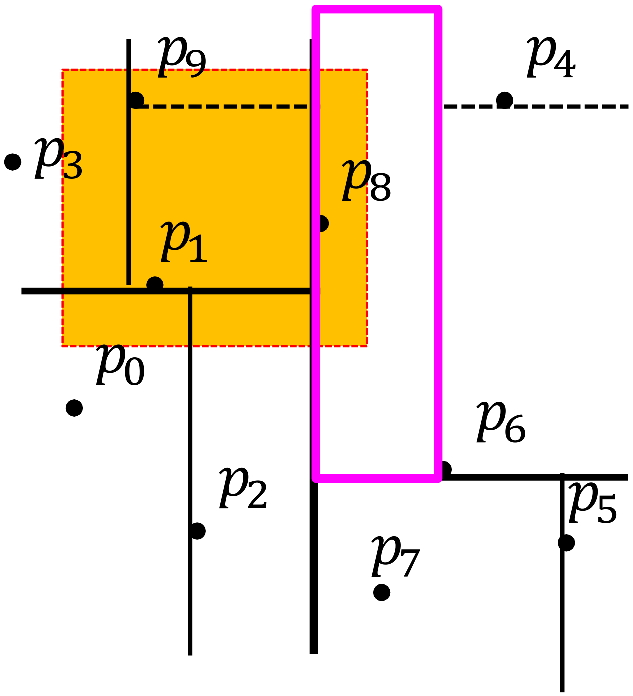

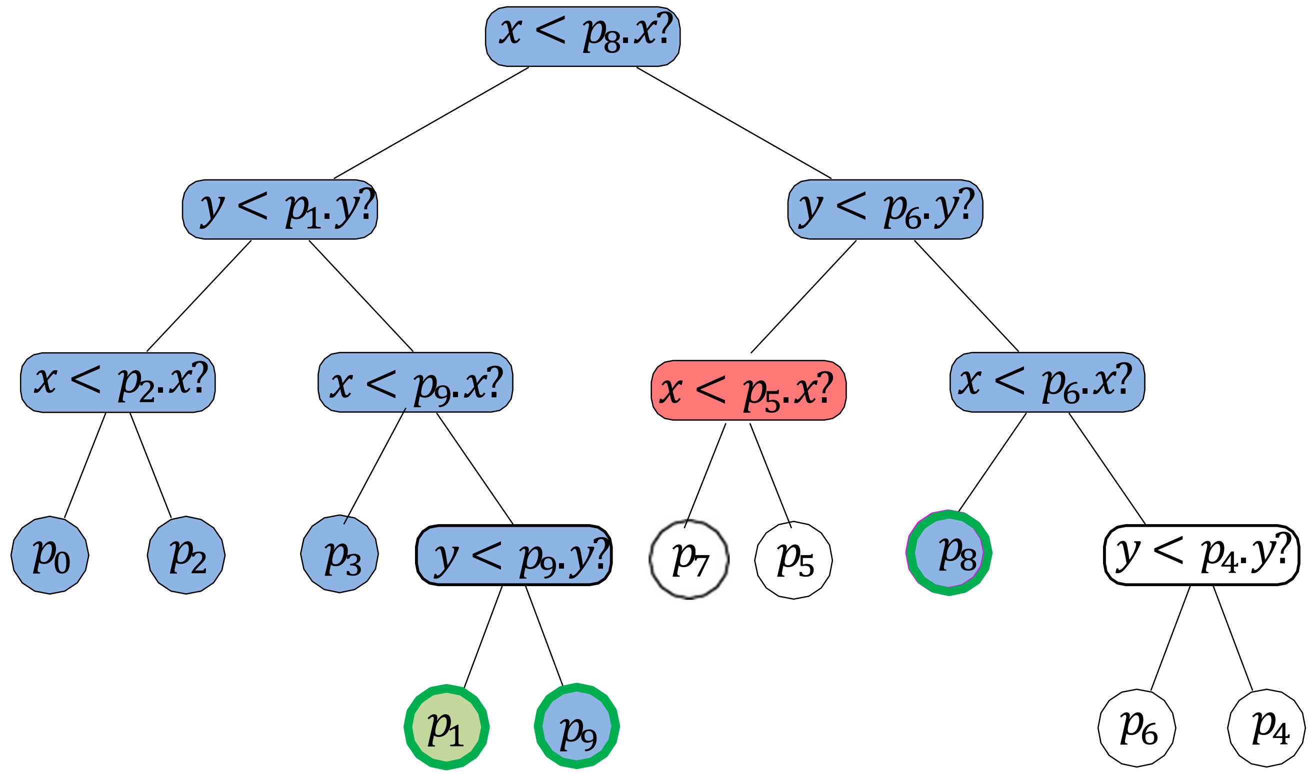

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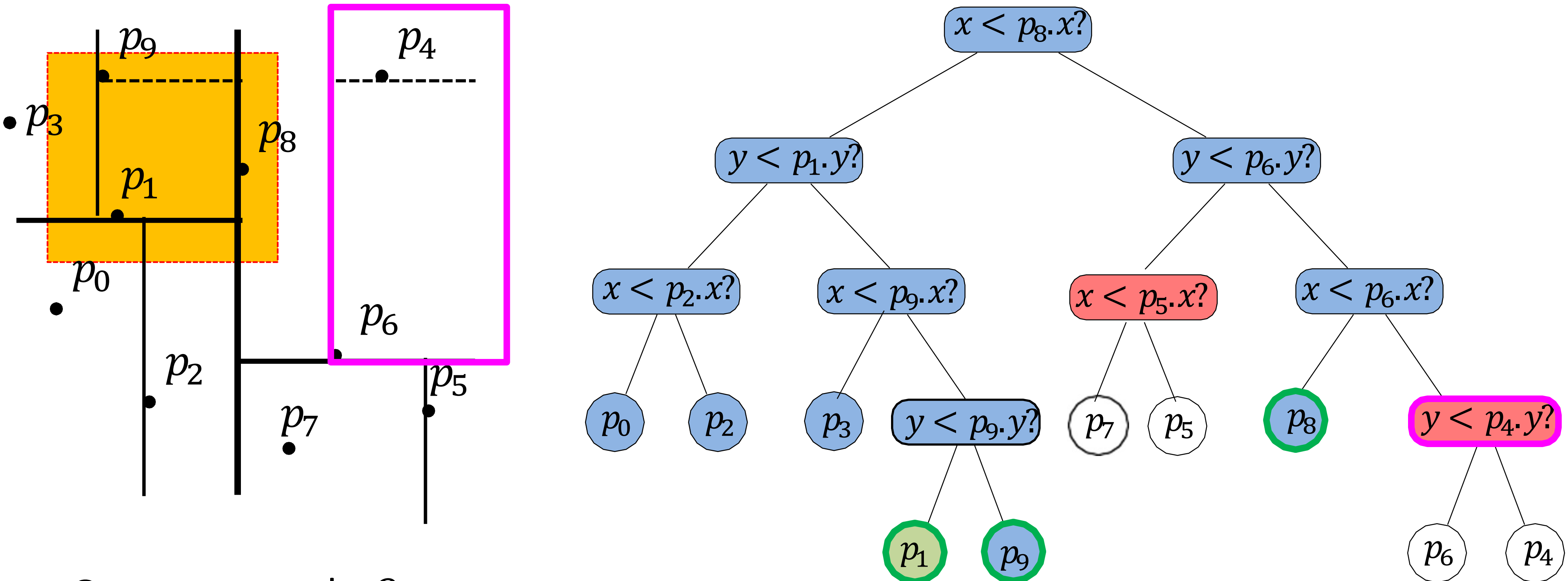

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kd-tree Range Search

kdTree::RangeSearch$(r \leftarrow \text{root},\ Q)$

r : root of kd-tree, Q: query rectangle

$R \leftarrow$ region associated with node r

if $R \subseteq Q$ **then**

report all points below r

return

if $R \cap Q = \emptyset$ **then return**

if r is a leaf **then**

$p \leftarrow$ point stored at r

if $p \in Q$ **return** p

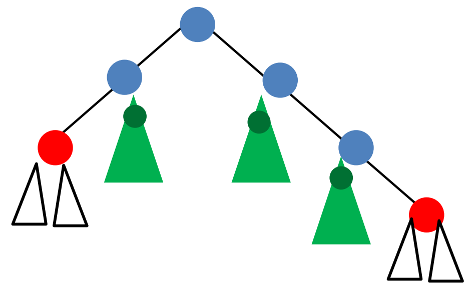
else return

for each child v of r **do**

kdTree::RangeSearch$(v,\ Q)$

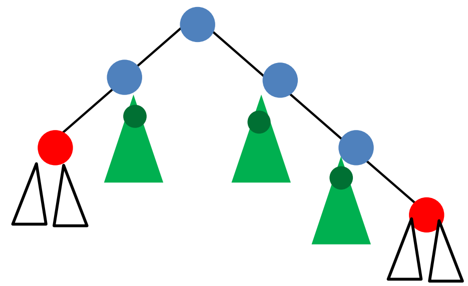
- We assume that each node stores its associated region
- To save space, we could instead pass the region as a parameter and compute the region for each child using the splitting line

kd-tree: Range Search Running Time



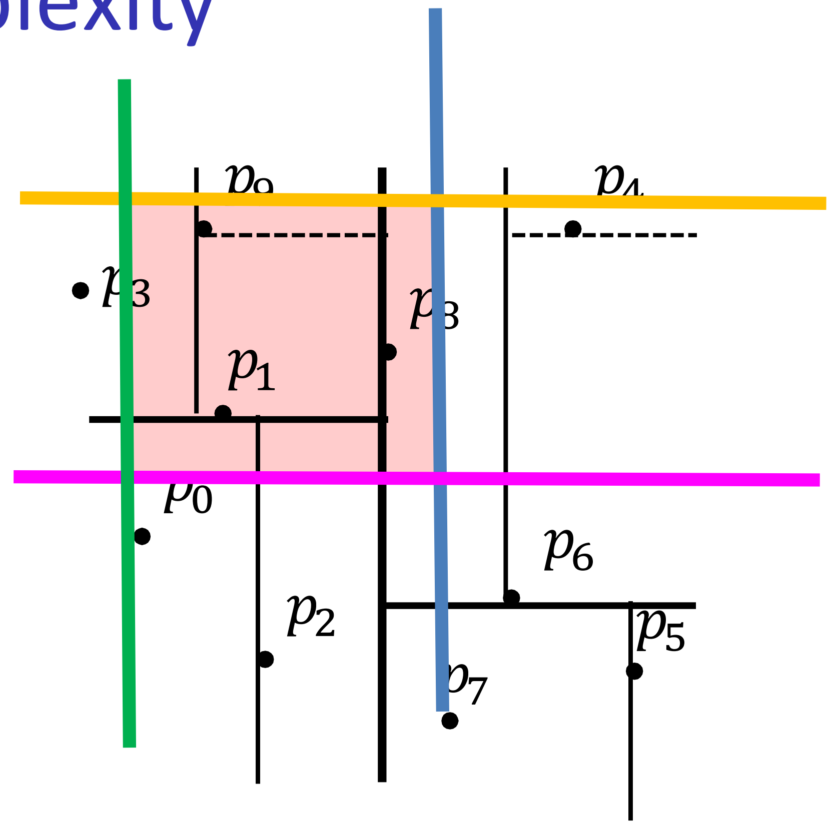
- Visit blue, red, and green nodes, constant work at each node
    - runtime is proportional to the number of blue, red, green nodes
- Green nodes form green subtrees
    - subtree root is the *topmost* green node
    - let v be the topmost green node
        - recall that s is the number of nodes in the output of range search
        - subtree of v is a kd-tree itself
            - number of internal nodes is 1 less than the number of leaves
        - at most s leaves over all green subtrees, and, therefore, at most $2s$ nodes over all green subtrees
    - number of green nodes is $O(s)$

kd-tree: Range Search Running Time



- Visit blue, red, and green nodes, constant time at each node
    - $O(s)$ of green nodes
- red nodes $\leq 2 \cdot$ blue nodes
        - each red node has a blue parent
    - for asymptotic runtime, enough to count blue nodes and add $O(s)$
- Let $B(n)$ is the number of blue nodes
    - if R corresponds to a blue node, neither $R \cap Q = \emptyset$ nor $R \subseteq Q$
    - regions that intersect Q but not completely inside Q
- Can show that $B(n)$ satisfies $B(n) \leq 2B\left(\frac{n}{4}\right) + O(1)$
    - resolves to $B(n) \in O(\sqrt{n})$
- Therefore, running time of range search is $O(s + \sqrt{n})$

kd-tree: Range Search Complexity

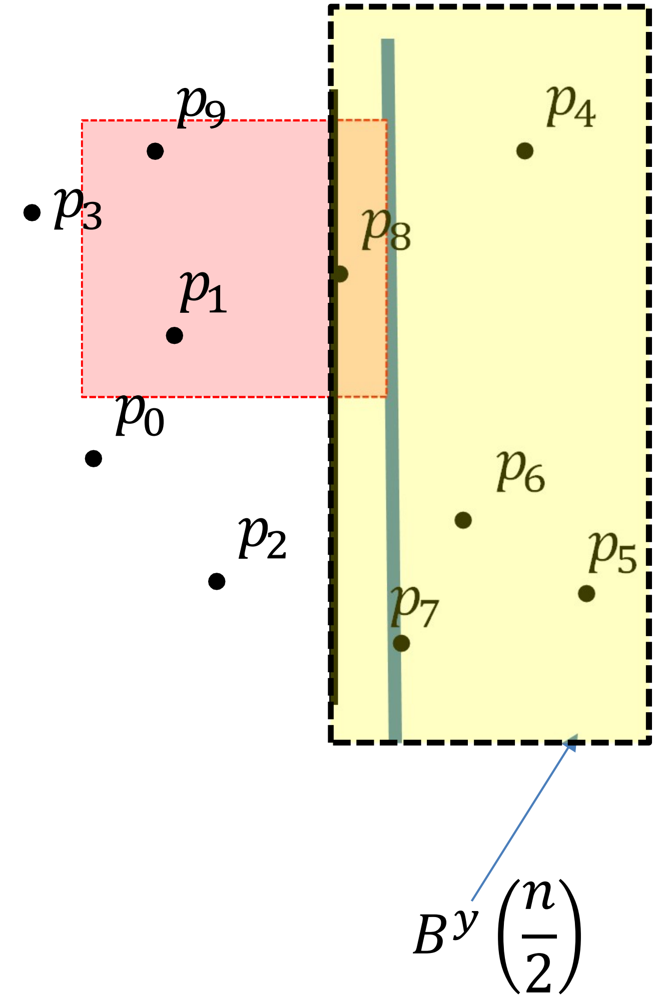


- search rectangle Q
- $B(n) =$ # regions intersecting Q but not completely inside Q
- $B(n) \leq$ # regions intersecting
  $+$ # regions intersecting
  $+$ # regions intersecting
  $+$ # regions intersecting
- Will look at # regions intersecting
- Other cases are handled similarly

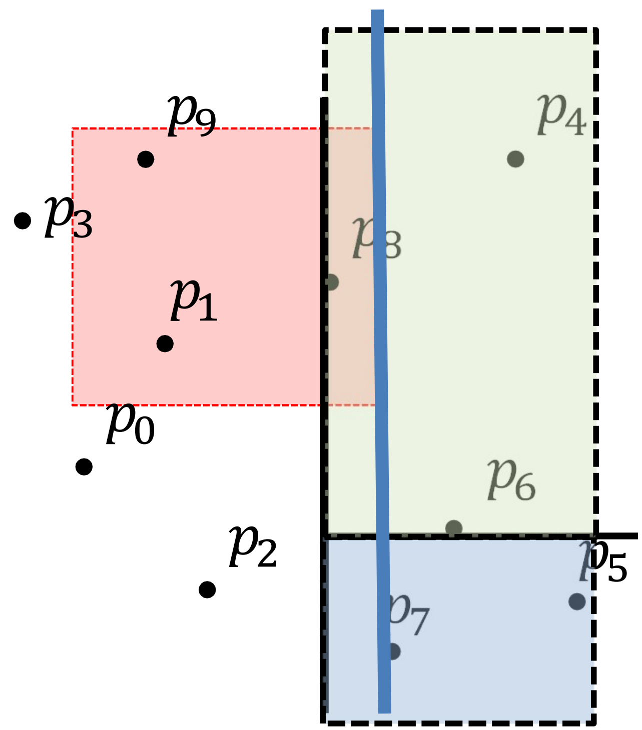
kd-tree: Range Search Complexity

- $B^x(n)$ = # regions intersected by ▌, if tree root split by x coordinate

- $B^x(n) = 1 + B^y\left(\frac{n}{2}\right)$
    - 1 for the root region R
    - root region is split in 2 by vertical line
    - ▌ can intersect only one of these regions



kd-tree: Range Search Complexity



- $B^x(n) =$ # regions intersected by , if tree root split by x coordinate

- $B^x(n) = 1 + B^y\left(\frac{n}{2}\right)$
  - 1 for the root region
  - root region is split in 2 by vertical line
  - can intersect only one of these regions

- Next, $B^y\left(\frac{n}{2}\right) = 1 + 2B^x\left(\frac{n}{4}\right)$
  - 1 for the root region
  - root region is split in 2 by horizontal line
  - can intersect both of these regions

- Combining, get recurrence $Q^x(n) = 2 + 2B^x\left(\frac{n}{4}\right)$
- Resolves to $B^x(n) \in O(\sqrt{n}\,)$

kd-tree: Higher Dimensions

- kd-trees for d-dimensional space
  - at depth 0 (the root) partition is based on the 1st coordinate
  - at depth 1 partition is based on the 2nd coordinate
  - …
  - at depth $d-1$ the partition is based on the last coordinate
  - at depth d start all over again, partitioning on 1st coordinate
- Storage $O(n)$
- Height $O(\log n)$
- Construction time $O(n\log n)$
- Range query time $O(s + n^{1-\frac{1}{d}})$
  - assumes that d is a constant

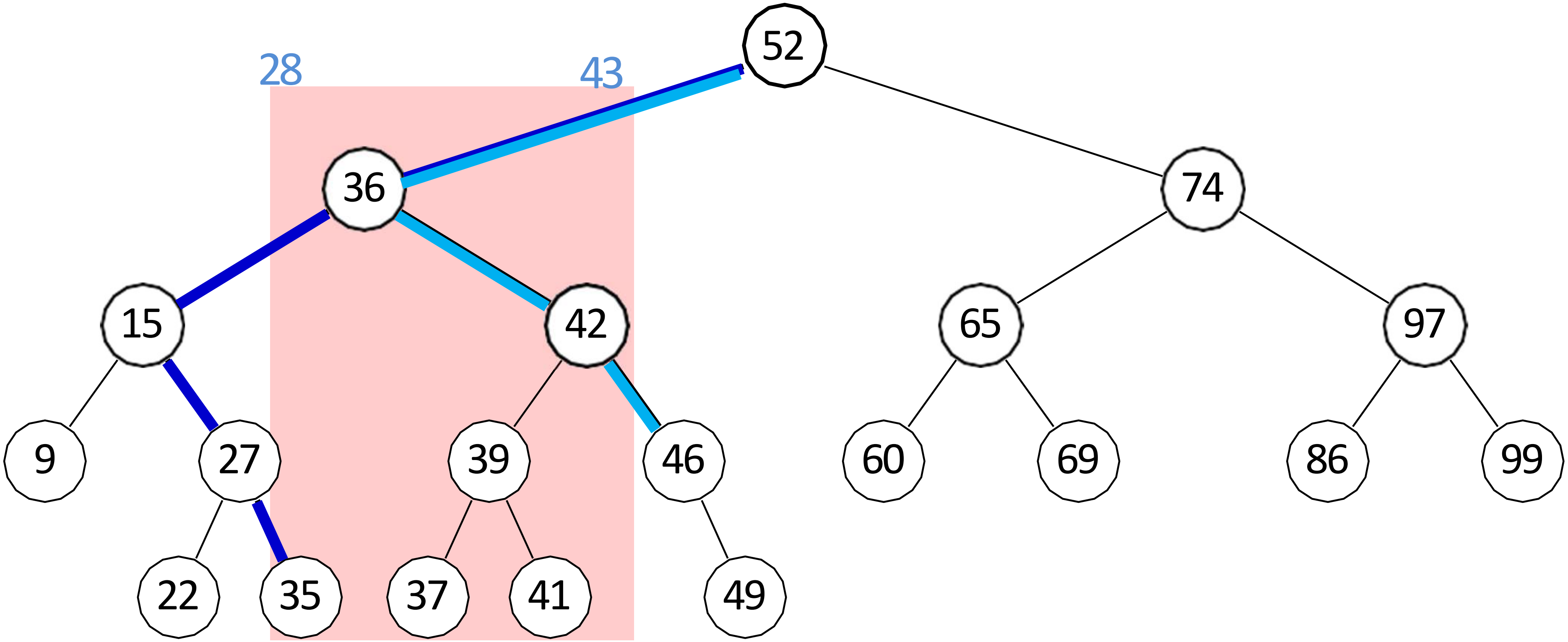
Outline

- Range-Searching in Dictionaries for Points
    - Range Search
    - Multi-Dimensional Data
    - Quadtrees
    - kd-Trees
    - Range Trees
    - Conclusion

Towards Range Trees

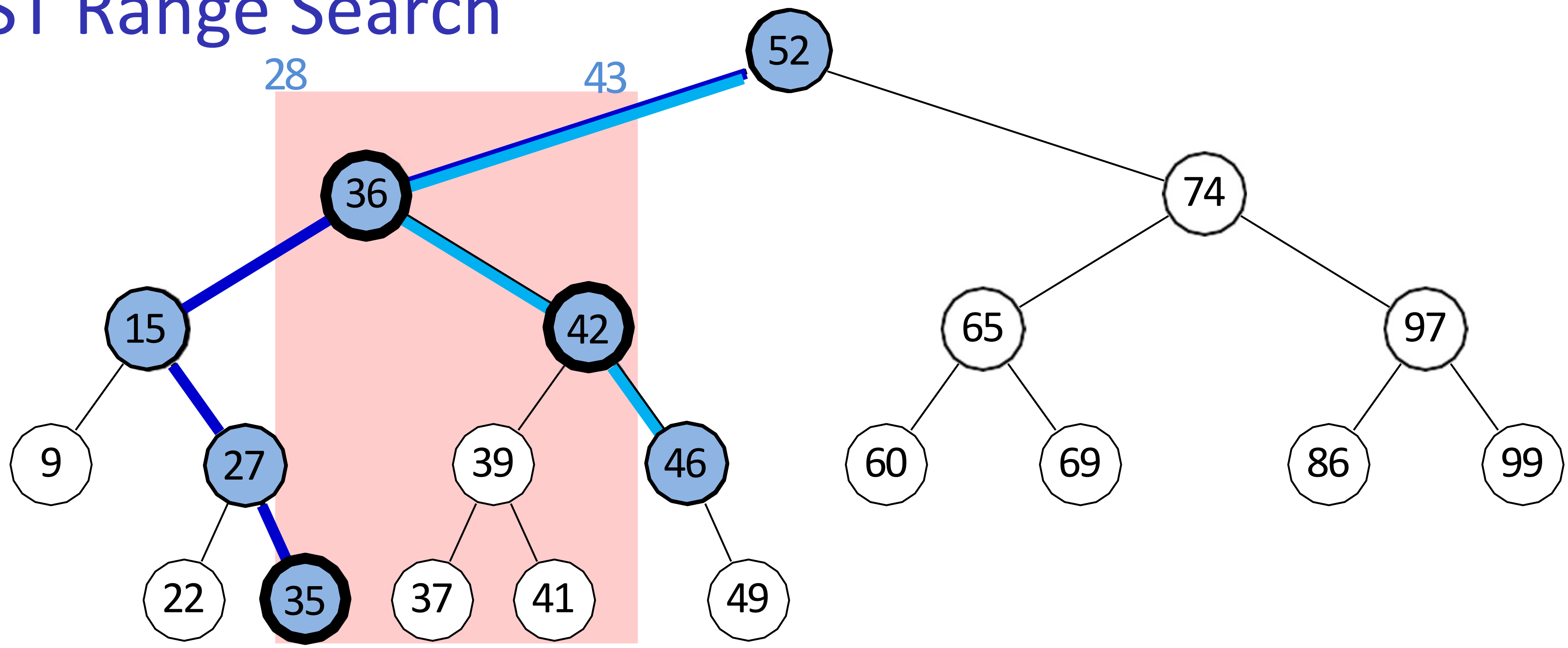
- Quadtrees and kd-trees
  - intuitive and simple
  - but both may be slow for range searches
  - quadtrees are also potentially wasteful in space
- Consider BST/AVL trees
  - efficient for one-dimensional dictionaries, if balanced
    - range search is also efficient
  - can we use ideas from BST/AVL trees for multi dimensional dictionaries?
- First let us consider range search in BST
  - all searches will be inclusive of the boundaries
  - *BST::RangeSearch*$(T, 28, 43)$
    - search includes both 28 and 43
      - easy to modify when one or both endpoints are excluded

BST Range Search



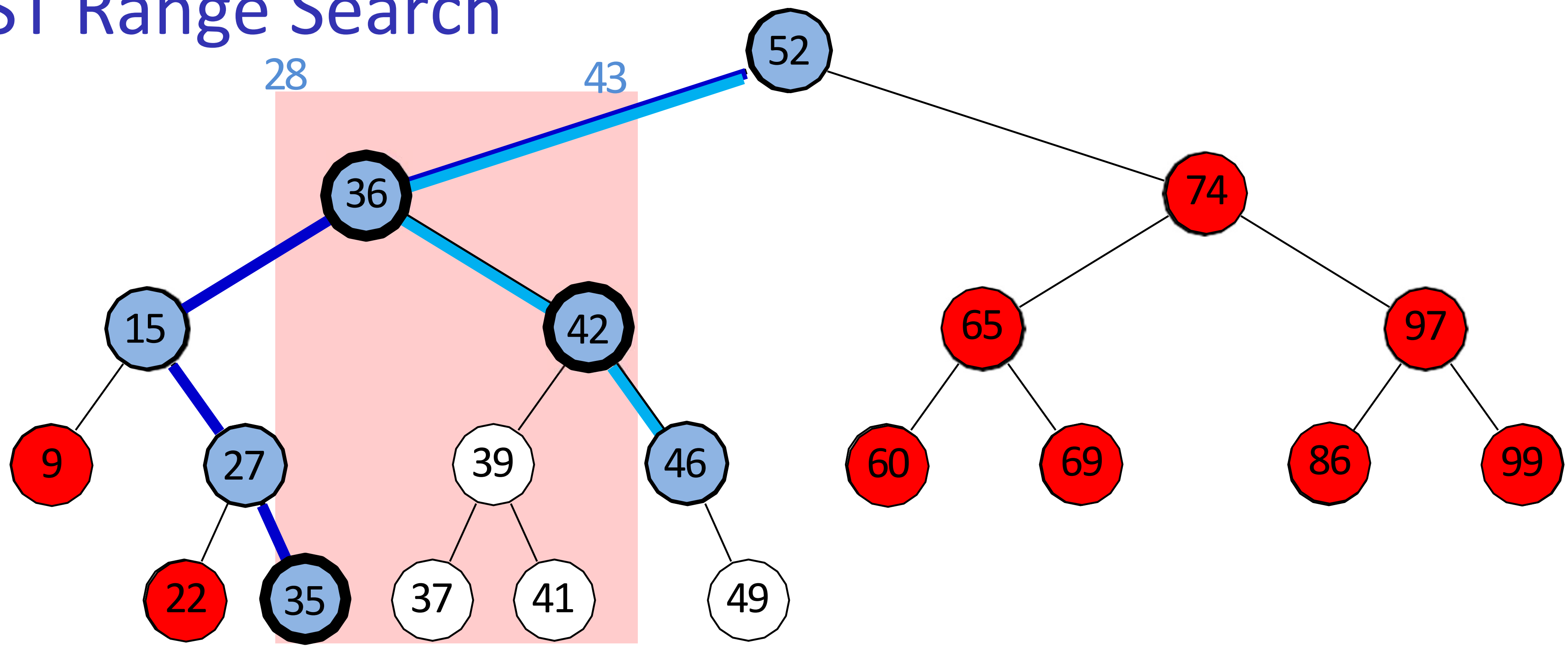
- $RangeSearch(T, 28, 43)$
- Search for left boundary k_1 : this gives path ***P*₁**
- Search for right boundary k_2 : this gives path ***P*₂**
- Nodes are partitioned into three groups: boundary, outside, inside

BST Range Search



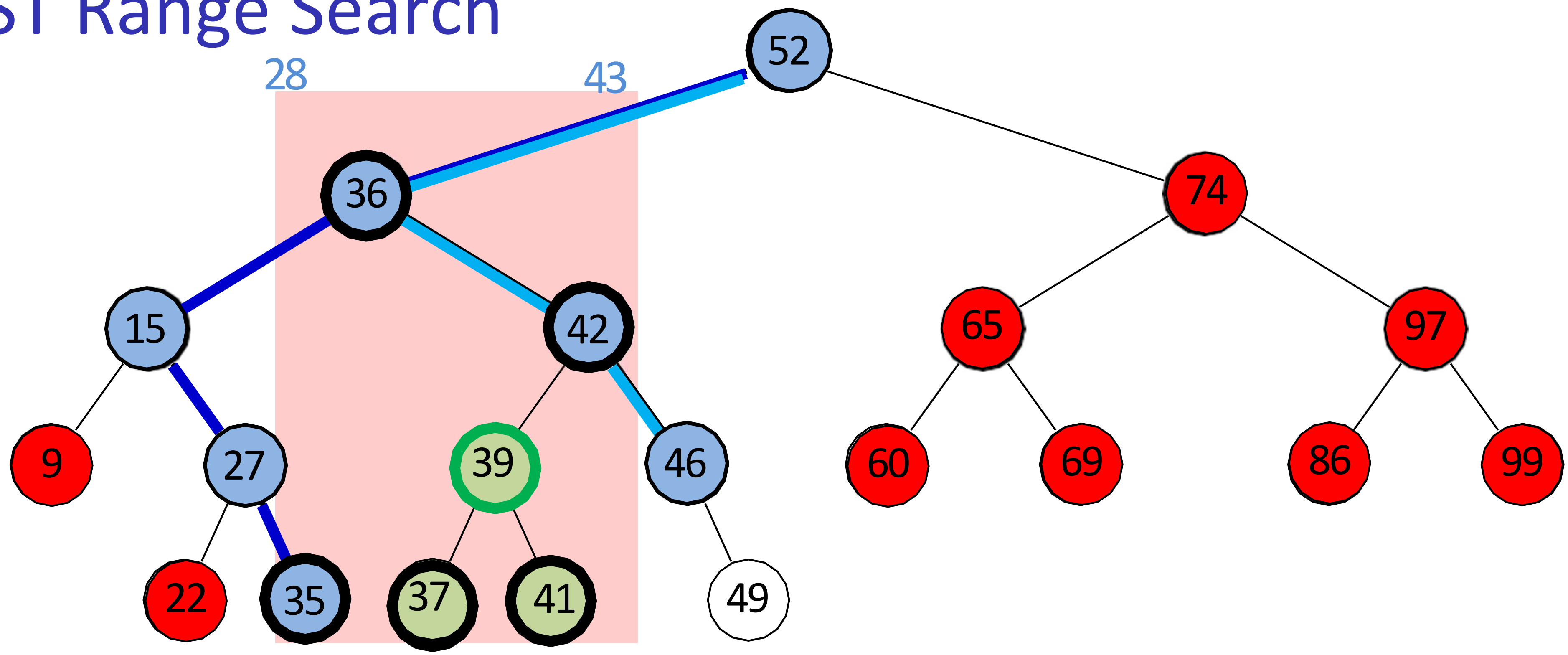
- Boundary nodes: nodes on P_1 and P_2
  - check if boundary nodes are in the search range

BST Range Search



- Boundary nodes: nodes on P_1 and P_2
  - check if boundary nodes are in the search range
- Outside nodes: nodes that are left of P_1 or right of P_2
  - not in search range, range search never examines them

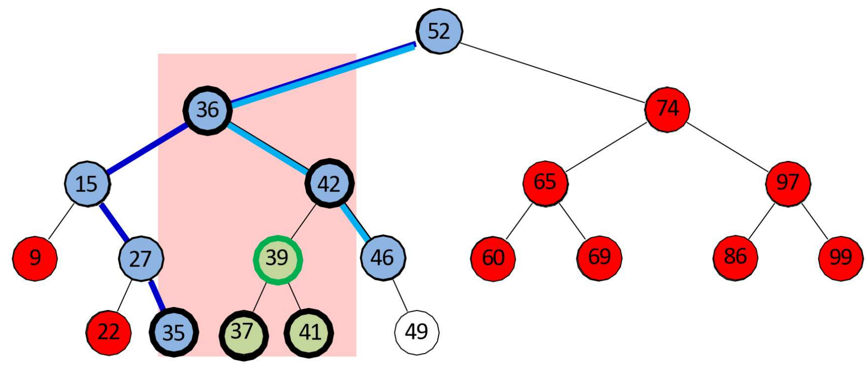
BST Range Search



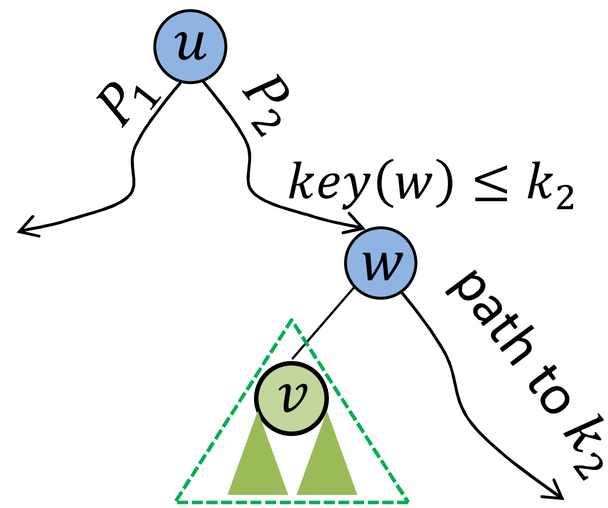
- Boundary nodes: nodes on P_1 and P_2
  - check if boundary nodes are in the search range
- Outside nodes: nodes that are left of P_1 or right of P_2
  - not in search range, range search never examines them
- Inside nodes: nodes that are right of P_1 and left of P_2
  - keep a list of ***topmost*** inside nodes
    - all descendants of topmost inside node are in the range, just report them

How to Find Top Inside Node

- v is a top inside node if
  - v is not is in P_1 or P_2
  - parent of v is in P_1 or P_2 (but not both)
  - if parent is in P_1, then v is right child
  - if parent is in P_2, then v is left child



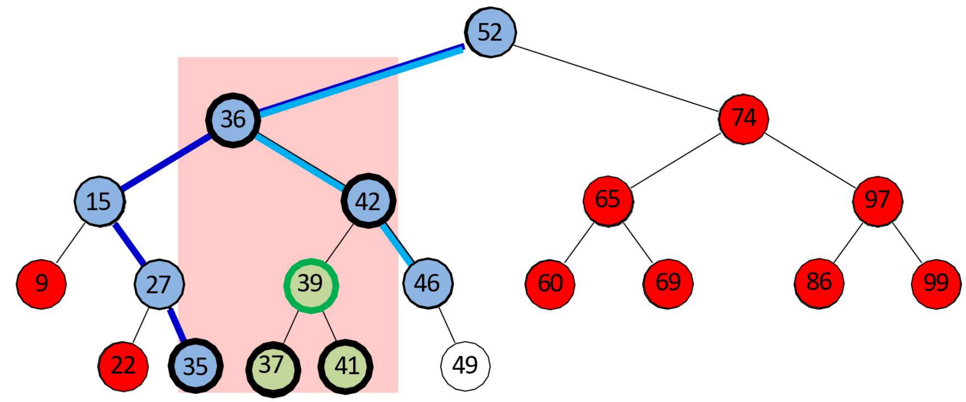
$k_1 \le key(u) < k_2$



$k_1 \le key(u) <$ everything $< key(w) \le k_2$

- Thus for each top inside node can report all descendants
  - top inside nodes are important for efficient $2D$ range search
  - also important if need to just count the number of points in the search range

BST Range Search Analysis

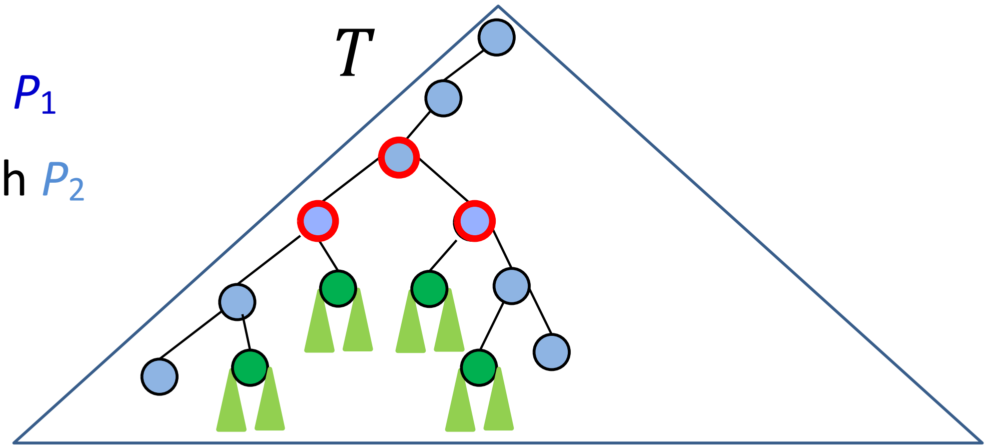


- Assume balanced BST
- Running time consists of
  1. search for path ***P*₁** is $O(\log n)$
  2. search for path ***P*₂** is $O(\log n)$
  3. check if boundary nodes in the range
     - $O(1)$ at each boundary node, there are $O(\log n)$ of them, $O(\log n)$ total time
  4. spend $O(1)$ at each topmost inside node
     - since each topmost inside node is a child of boundary node, there are at most $O(\log n)$ topmost inside nodes, so total time $O(\log n)$
  5. report descendants in subtrees of all topmost inside nodes
     - topmost nodes are disjoint, so #descendants for inside topmost nodes is at most s, output size

$$\sum_{\substack{\text{topmost inside} \\ \text{node } v}} \#\text{descendants of } v \leq s$$

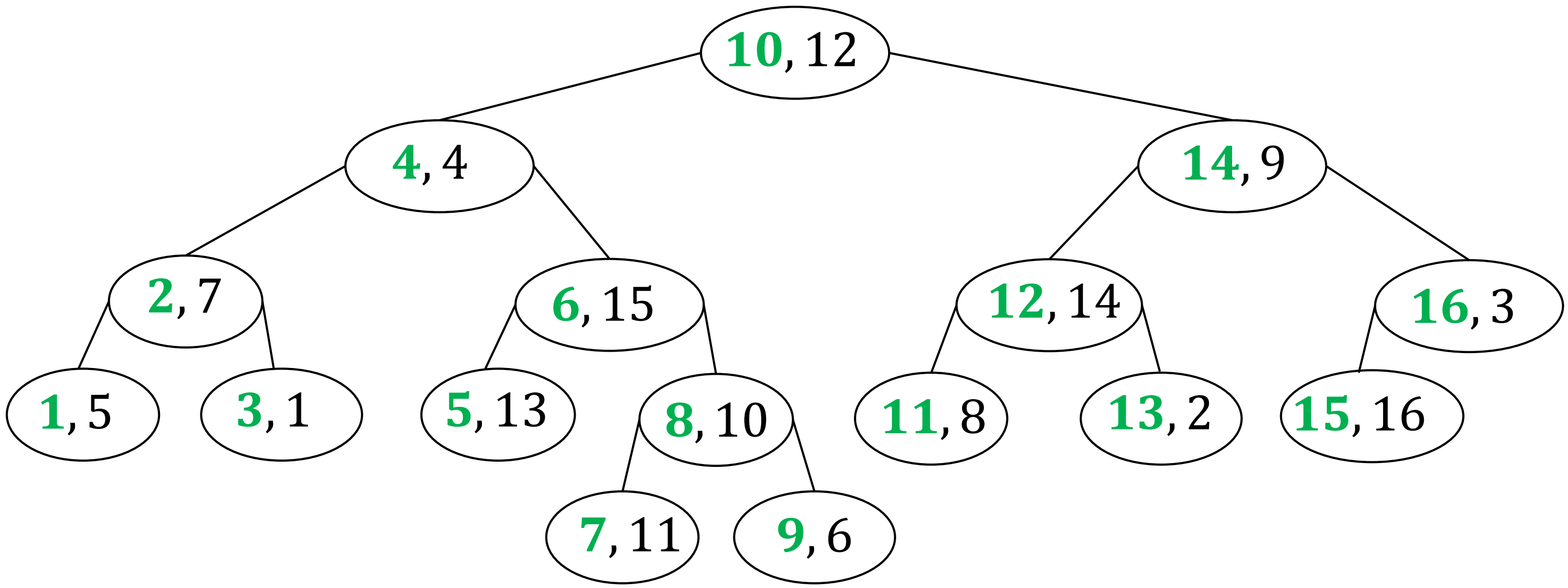
- Total time $O(s + \log n)$

BST Range Search Summary



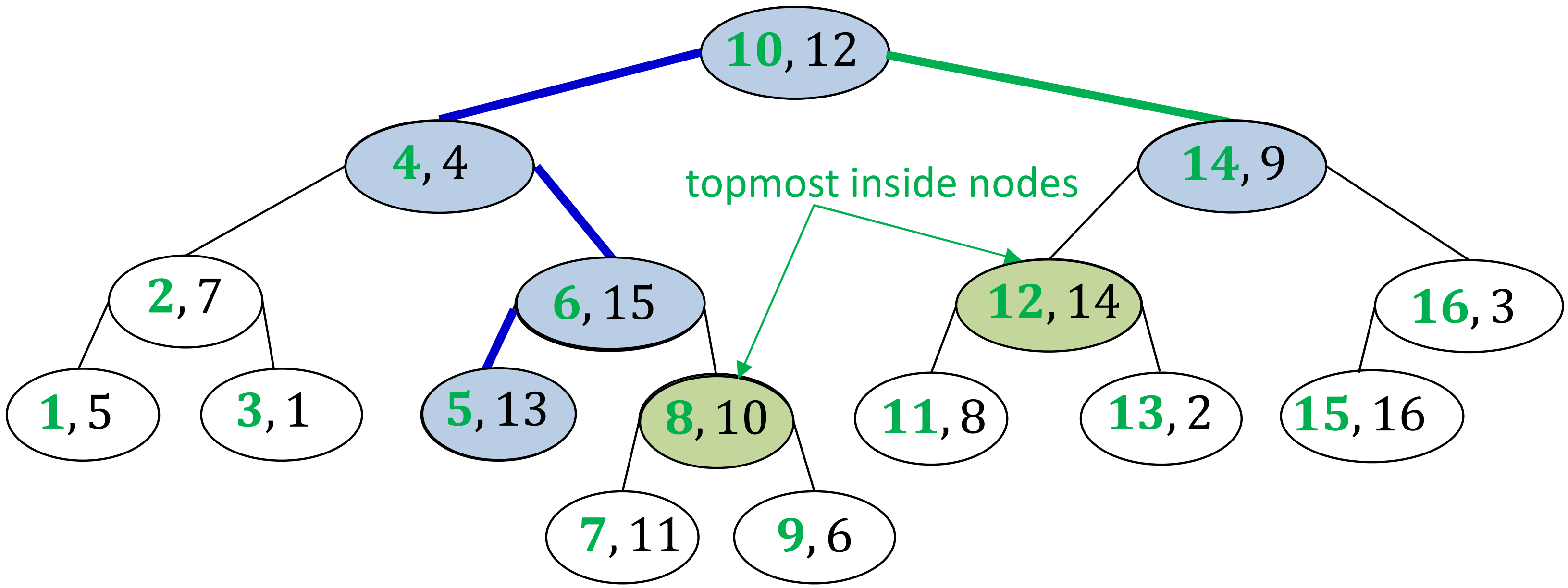
- Search for k_1: this gives left boundary path P_1
- Search for k_2: this gives right boundary path P_2
- Find all topmost inside nodes
  - not in P_1 or P_2
  - left children of nodes in P_2
  - right children of nodes in P_1
- Inside node (which is not a topmost inside) is in a subtree of some topmost inside node
- Set of inside nodes = union disjoint subtrees rooted at topmost inside nodes
- To output nodes in the search range
  - test each node in P_1, P_2 and report if in range
  - go over all topmost inside nodes and report all nodes in their subtree

2D Range Tree Motivation



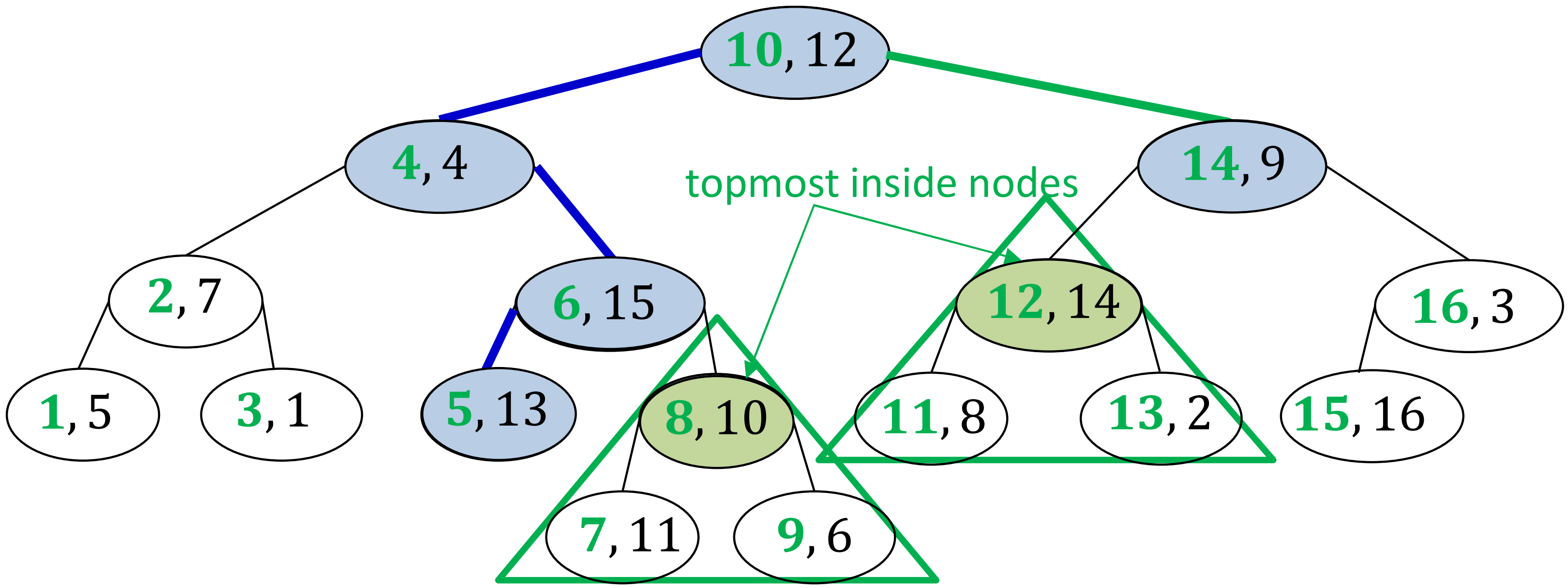
- Have a set of 2D points
  - $S = \{(1,5), (2,7), (3,1), (4,4), (5,13), (6,15)(7,11), (8,10), (9,6), (10,12), (11,8), (12,14), (13,2), (14,9), (15,16), (16,3)\}$
- Example of 2D range search
- *BST-RangeSearch*$(T, 5, 14, 5, 9)$
  - find all points with $5 \le x \le 14$ and $5 \le y \le 9$
- Construct BST with x-coordinate key
  - recall that points are in general positon, so all x-keys are distinct
    - for any (x_1, y_1) and (x_2, y_2) in our set of points, $x_1 \neq x_2$
  - can search efficiently based only on x-coordinate

2D Range Tree Motivation



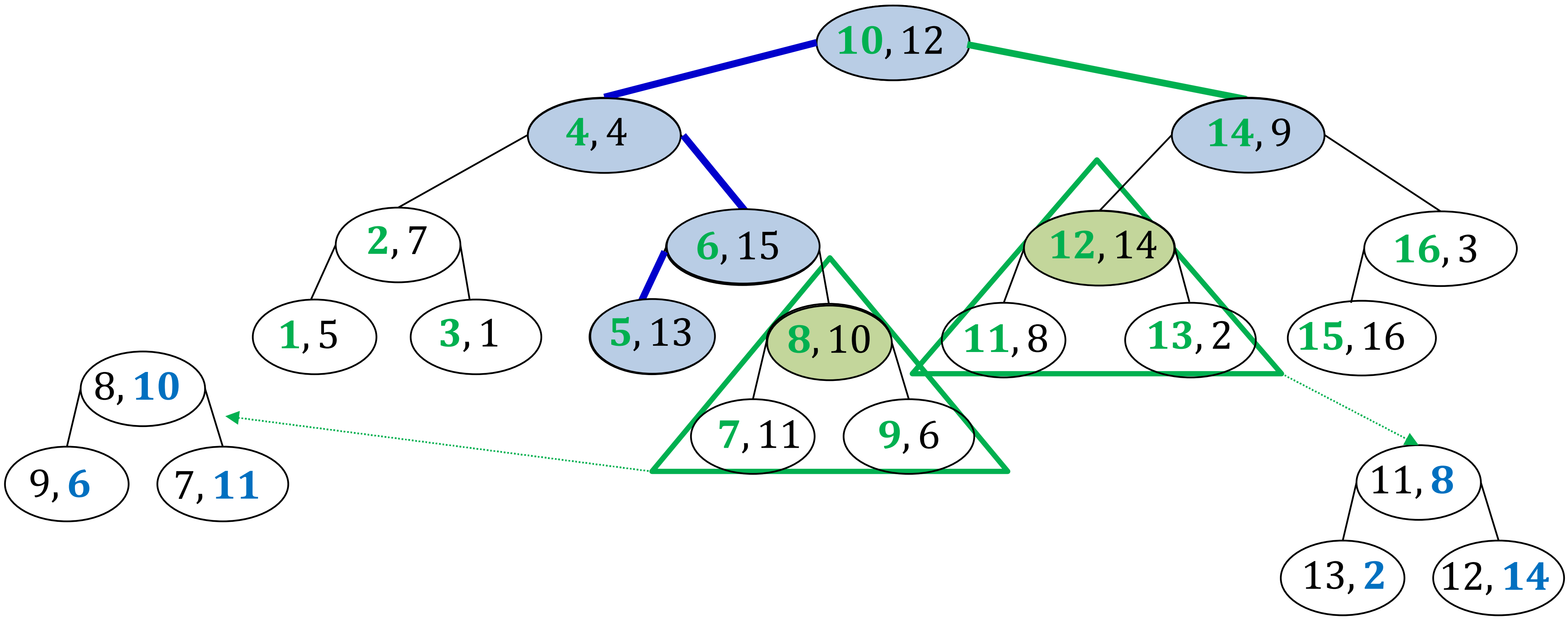
- Consider $2D$ range search *BST-RangeSearch*$(T, 5, 14, 5, 9)$
- Could first perform *BST-RangeSearch*$(T, 5, 14)$
  - let A be the set of nodes *BST-RangeSearch*$(T, 5, 14)$ returns
    - $A = \{(10,12), (6,15), (5,13), (14,9), (8,10), (7,11), (9,6), (12,14), (11,8), (13,2)\}$
  - let B be the set of nodes *BST-RangeSearch*$(T, 5, 14, 5, 9)$ should return
    - $B \subseteq A$
  - Need to go over all nodes in A and check if their y-coordinate is in valid range, $O(|A|)$
    - could be very inefficient
    - for example, $|A|$ can be, say $\Theta(n)$ and $|B|$ could be $O(1)$
      - $O(n)$, as bad as exhaustive search and worse than kd-trees search, $O(|B| + \sqrt{n})$

2D Range Tree Motivation



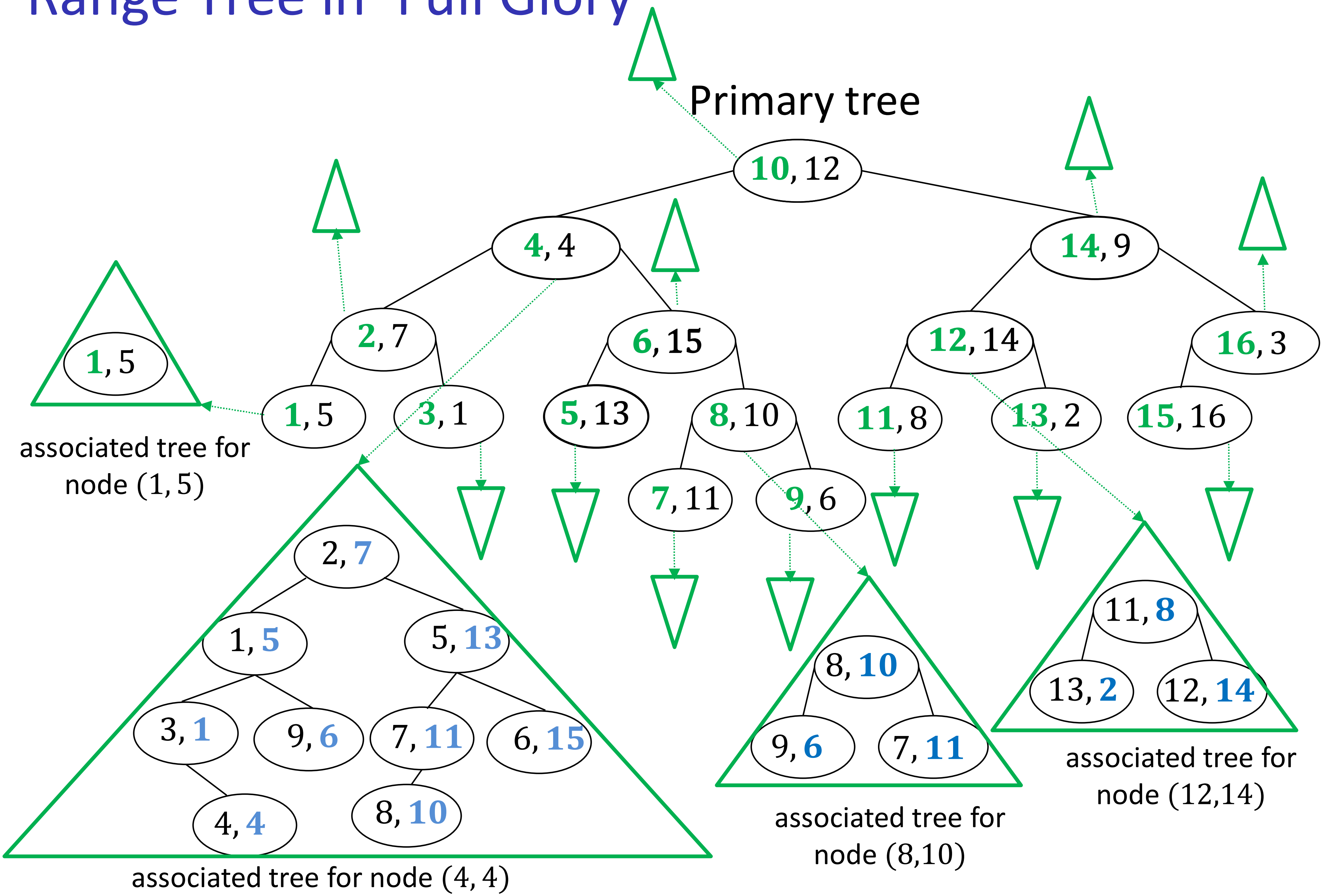
- Consider $2D$ range search *BST-RangeSearch*$(T, 5, 14, 5, 9)$
- First perform only **partial** *BST-RangeSearch*$(T, 5, 14)$
  - find boundary and topmost inside nodes, takes $O(\log n)$ time
- Next
  - for boundary nodes, check if **both** x and y coordinates are in the range, takes $O(\log n)$ time as there are $O(\log n)$ boundary nodes
  - inside nodes are stored in $O(\log n)$ subtrees, with a topmost inside node as a root of each subtree
    - if we could search these subtrees, time would be very efficient
    - however these subtrees do not support efficient search by y coordinate

2D Range Tree Motivation

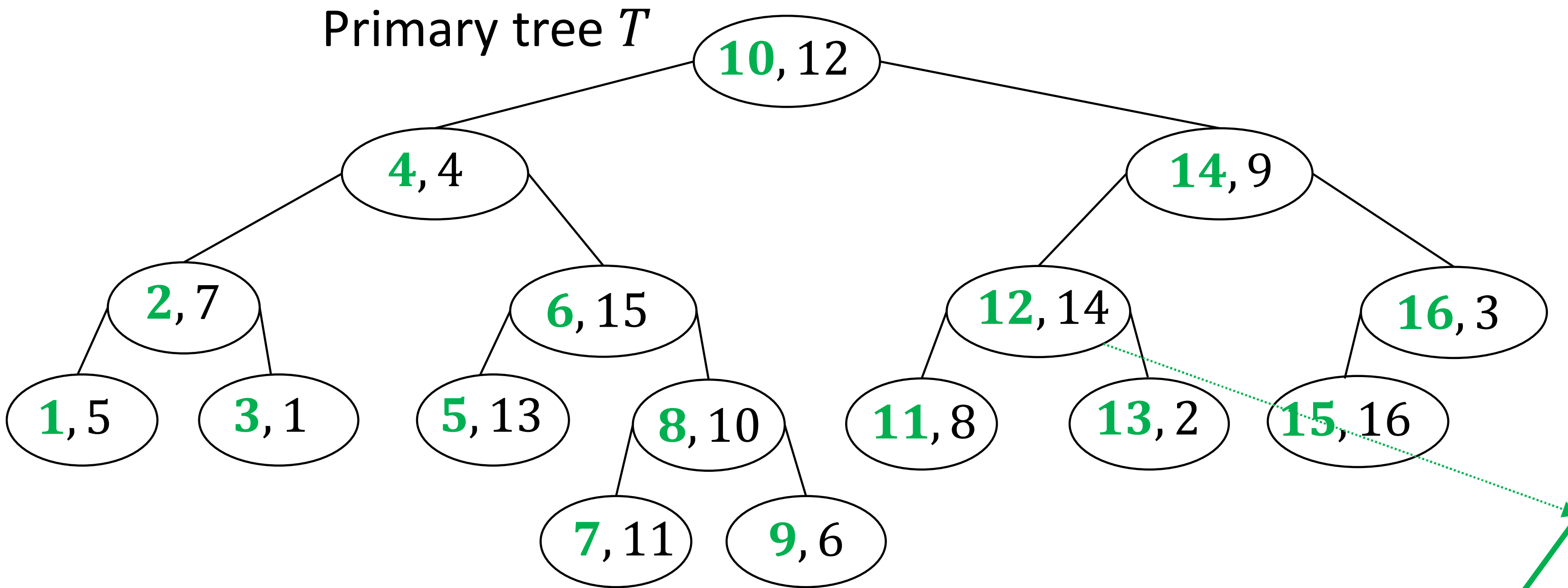


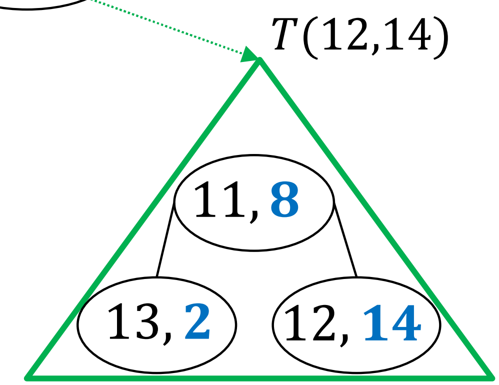
- Need to search subtrees by y-coordinate, but they are x-coordinate based
- Brute-force solution
  - need an associate balanced BST tree for each node v
    - stores same items as the main (primary) subtree rooted at node v
    - but key is y-coordinate

Range Tree in 'Full Glory'



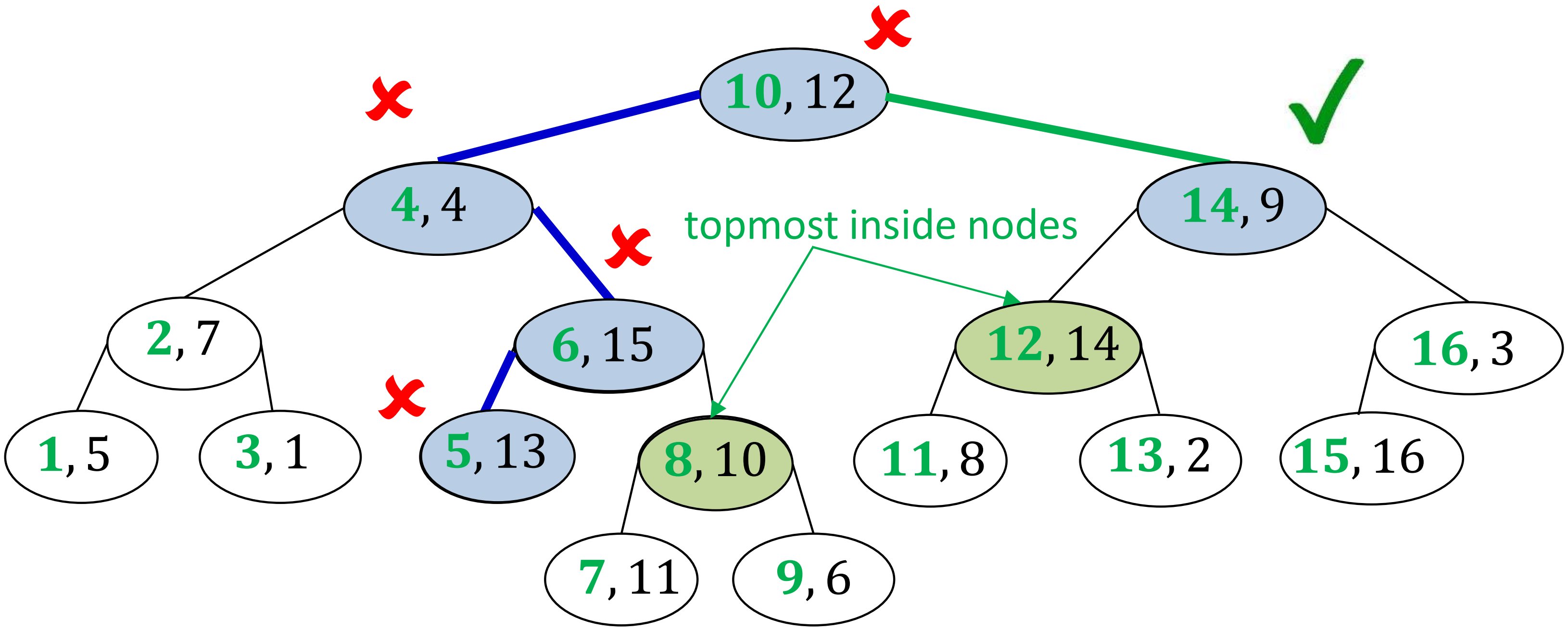
2-dimensional Range Trees Full Definition





- Points $S = \{(x_0, y_0), (x_1, y_1), \ldots, (x_{n-1}, y_{n-1})\}$
- Range tree is a tree of trees (a *multi-level* data structure)
  - Primary structure
    - balanced BST T storing S and uses x-coordinates as keys
    - assume T is balanced, so height is $O(\log n)$
  - Each node v of T stores an associated tree $T(v)$, which is a balanced BST
    - let $S(v)$ be all descendants of v in T, including v
    - $T(v)$ stores $S(v)$ in BST, using y-coordinates as key
      - note that v is not necessarily the root of $T(v)$

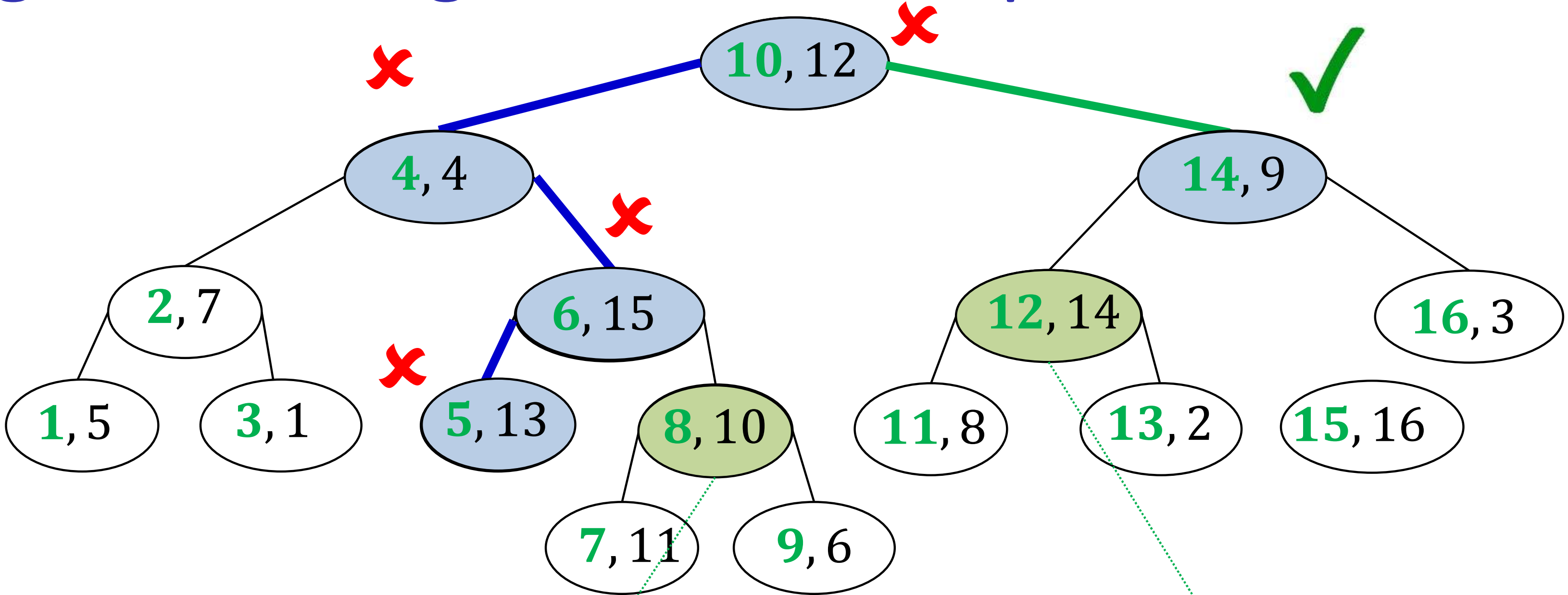
Range search in 2D Range Tree Overview



- *RangeTree::RangeSearch*(T, x_1, x_2, y_1, y_2)
  - *RangeTree::RangeSearch*$(T, 5, 14, 5, 9)$

1. Perform *modified BST-RangeSearch*$(T, 5, 14)$
   - find boundary and topmost inside nodes, but do not go through the inside subtrees
   - modified version takes $O(\log n)$ time
     - does not visit all the nodes in valid range for *BST-RangeSearch*$(T, 5, 14)$
2. Check if boundary nodes have valid x-coordinate **and** valid y-coordinate
3. For every topmost inside node v, search in associated tree *BST::RangeSearch*$(T(v), 5, 9)$

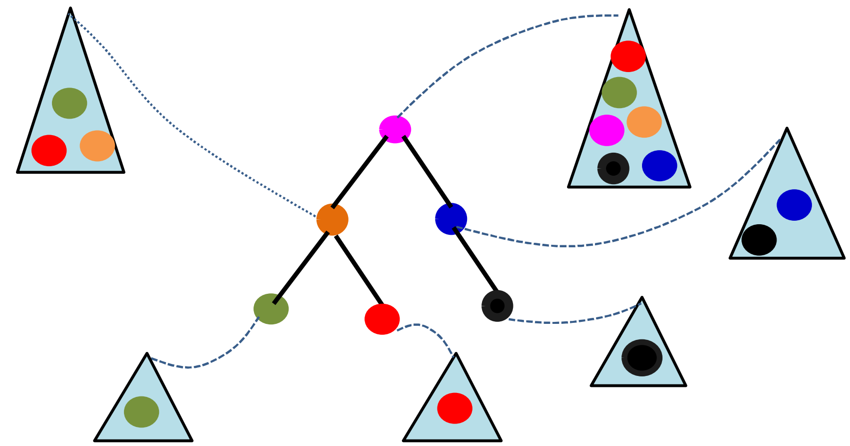
Range Tree Range Search Example Finished



- *RangeTree::RangeSearch*$(T, 5, 14, 5, 9)$
- For every topmost inside node v, search in associated tree *BST-RangeSearch*$(T(v), 5, 9)$

BST-rangeSearch$(T(8,10), 5,9)$ *BST-RangeSearch*$(T(12,14), 5,9)$

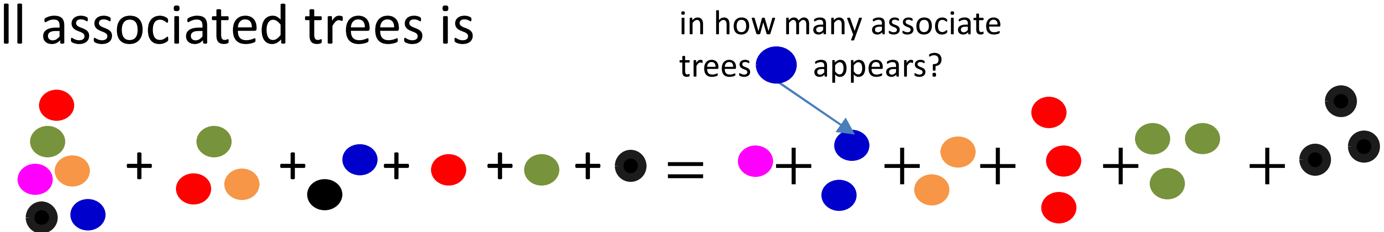
Range Tree Space Analysis



- Primary tree T uses $O(n)$ space
- For each v, associated tree $T(v)$ uses $O(|T(v)|)$ space

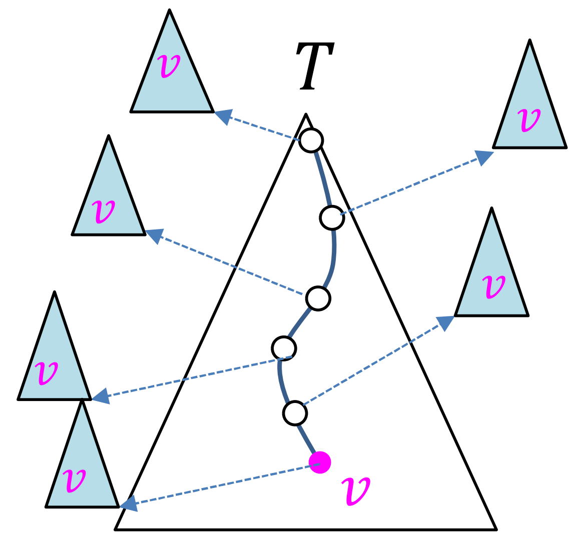
- Space for all associated trees is

$$\sum_{v\in T}|T(v)| =$$



$$= \sum_{v\in T} \underbrace{\#\text{of ancestors of } v}_{\leq c\log n}$$

$$\leq \sum_{v\in T} c\log n = cn\log n$$



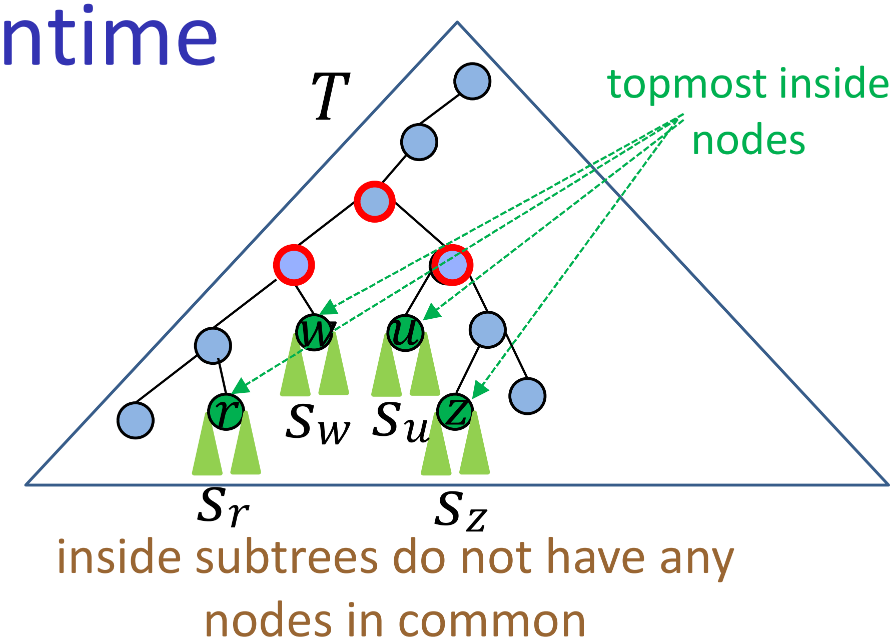
#of ancestors of v

- Space is $O(n\log n)$
  - in the worst case, have $n/2$ leaves at the last level, and space needed is $\Theta(n\log n)$

Range Trees: Dictionary Operations

- Search(x, y)
  - search by x coordinate in the primary tree T
- Insert(x, y)
  - first, insert point by x-coordinate into the primary tree T
  - then walk up to root and insert point by y-coordinate in *all* $T(v)$ of nodes v on path to root
- Delete
  - analogous to insertion
- **Problem**
  - want binary search trees to be balanced
  - if we use AVL-trees, it makes insert/delete very slow
    - rotations change primary tree structure and require rebuilding of associate trees
  - instead of rotations, can allow certain imbalance, rebuild entire subtree if imbalance becomes too large
    - no details

Range Trees: Range Search Runtime



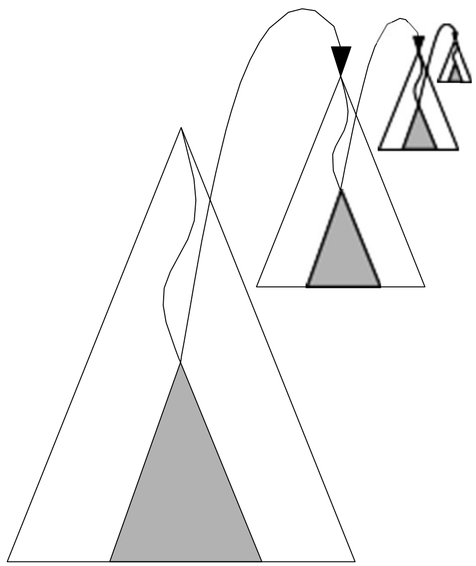
- Find boundary nodes in the primary tree and check if keys are in the range
  - $O(\log n)$
- Find topmost inside nodes in primary tree
  - $O(\log n)$
- For each topmost inside node v, perform range search for y-range in associate tree
  - $O(\log n)$ topmost inside nodes
  - let s_v be #items returned for the subtree of topmost node v
  - running time for one search is $O(\log n + s_v)$

$$\sum_{\substack{\text{topmost inside}\\ \text{node } v}} c(\log n + s_v) = \underbrace{\sum_{\substack{\text{topmost inside}\\ \text{node } v}} c\log n}_{O(\log^2 n)} + \underbrace{\sum_{\substack{\text{topmost inside}\\ \text{node } v}} cs_v}_{\leq cs}$$

- Time for range search in range tree: $O(s + \log^2 n)$
  - can make this even more efficient, but this is beyond the scope of the course

Range Trees: Higher Dimensions

- Range trees can be generalized to d -dimensional space
  - space $O(n\,(\log n)^{d-1})$
  - construction time $O(n\,(\log n)^{d})$
  - range search time $O(s + (\log n)^{d})$
- Note: d is considered to be a constant
- Space-time tradeoff compared to kd trees



Range Search Data Structures Summary

- Quadtrees
  - simple, easy to implement insert/delete (i.e. dynamic set of points)
  - work well only if points evenly distributed
  - wastes space, especially for higher than two dimensions
- kd-trees
  - linear space
  - range search is $O(s + \sqrt{n})$
  - inserts/deletes destroy balance and range search time
    - fix with occasional rebuilt
- Range trees
  - fastest range search $O(\log^2 n + s)$
  - wastes some space
  - insert and delete destroy balance, but can fix this with occasional rebuilt