RANGE TREES AND PRIORITY SEARCH TREES

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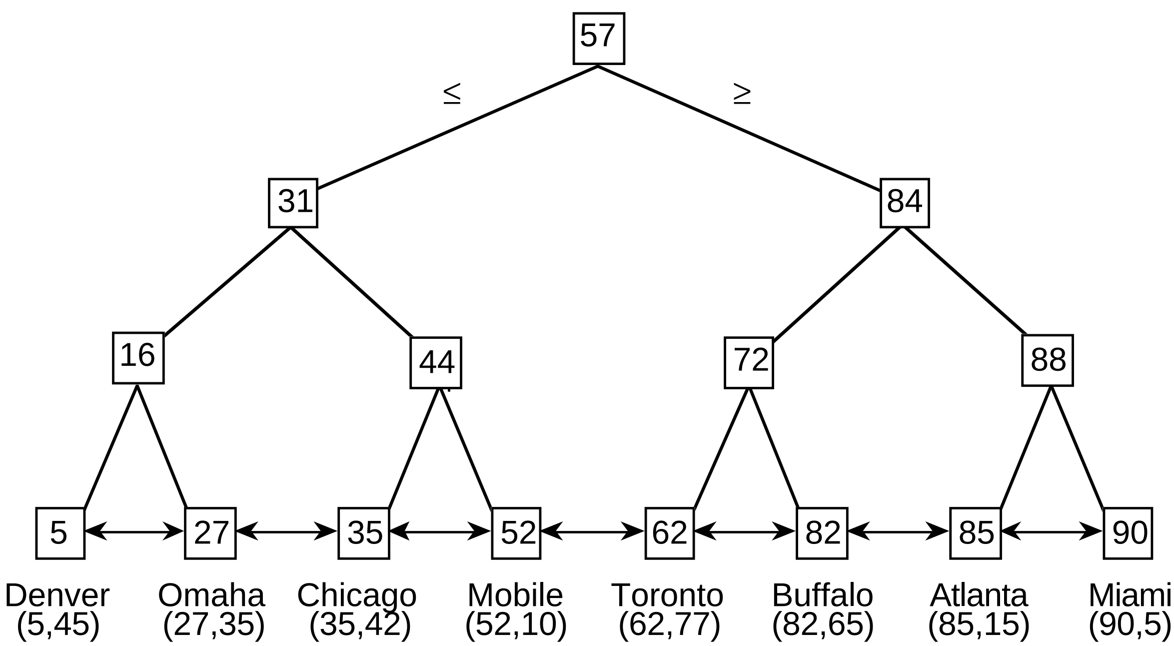
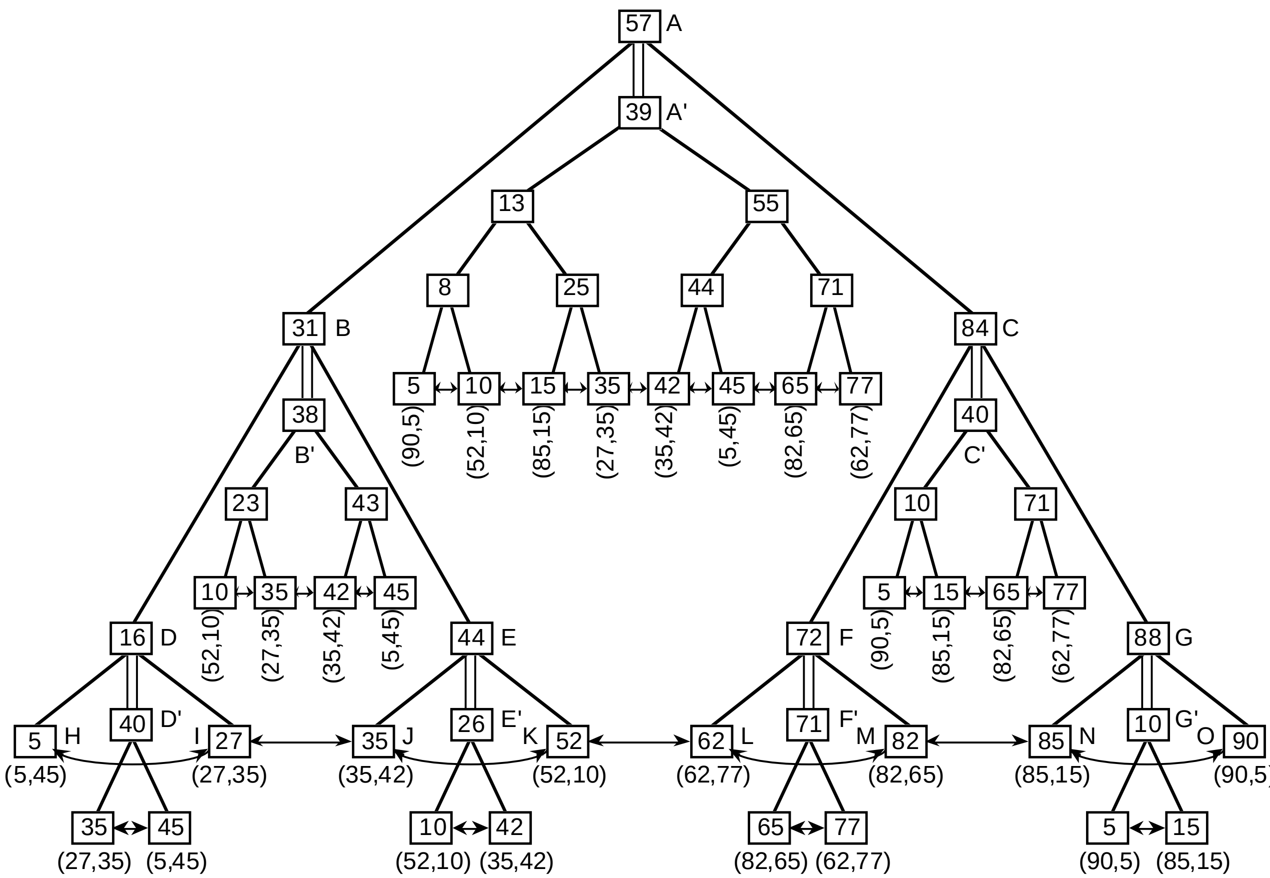
RANGE TREES

- Balanced binary search tree
- All data stored in the leaf nodes
- Leaf nodes linked in sorted order by a doubly-linked list
- Searching for [B : E]
  1. find node with smallest value ≥B or largest ≤B
  2. follow links until reach node with value >E
- $O(\log_2 N + F)$ time to search, $O(N \cdot \log_2 N)$ to build, and $O(N)$ space for N points and F answers
- Ex: sort points in 2-d on their x coordinate value



2-D RANGE TREES

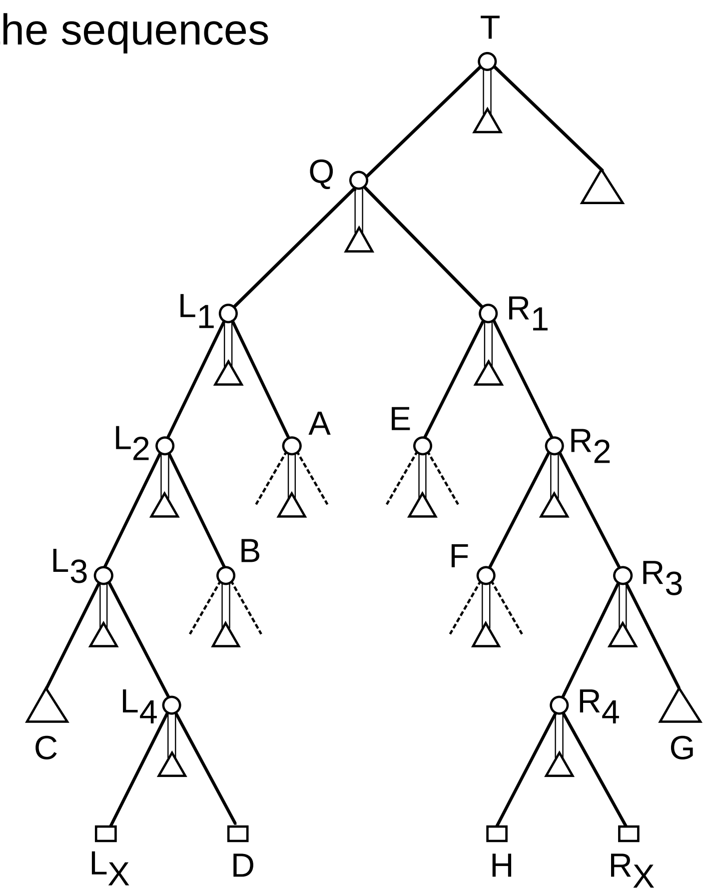
- Binary tree of binary trees
- Sort all points along one dimension (say *x*) and store them in the leaf nodes of a balanced binary tree such as a range tree (single line)
- Each nonleaf node contains a 1-d range tree of the points in its subtrees sorted along *y* (double lines)
- Ex:



- Actually, don't need the 1-d range tree in *y* at the root and at the sons of the root

SEARCHING 2-D RANGE TREES ([BX:EX],[BY:EY])

1. Search tree T for nodes BX and EX
   - find node LX with a minimum value ≥ BX
   - find node RX with a maximum value ≤ EX
2. Find their nearest common ancestor Q
3. Compute {L_i} and {R_i}, the sequences of nodes forming the paths from Q to LX and RX, respectively (including LX and RX but excluding Q)
   - LEFT(P) and RIGHT(P) are sons of P
   - MIDRANGE(P) discriminates on *x* coordinate value
   - RANGE_TREE(P) denotes the 1-d range tree stored at P
4. For each element in the sequences {L_i} and {R_i} do



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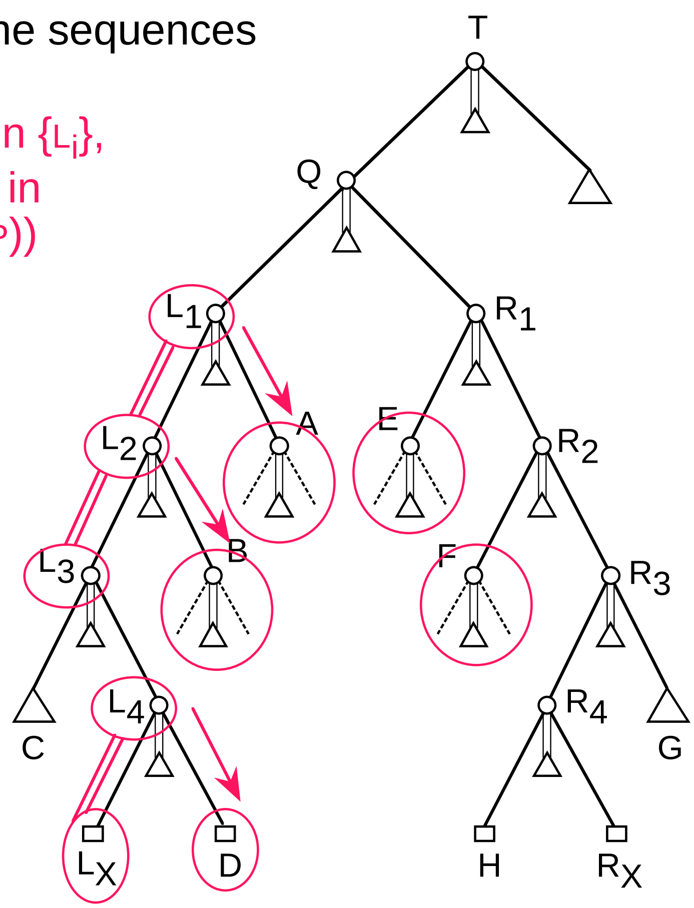
   - if P and LEFT(P) are in $\{L_i\}$, then look for [BY,EY] in RANGE_TREE(RIGHT(P))



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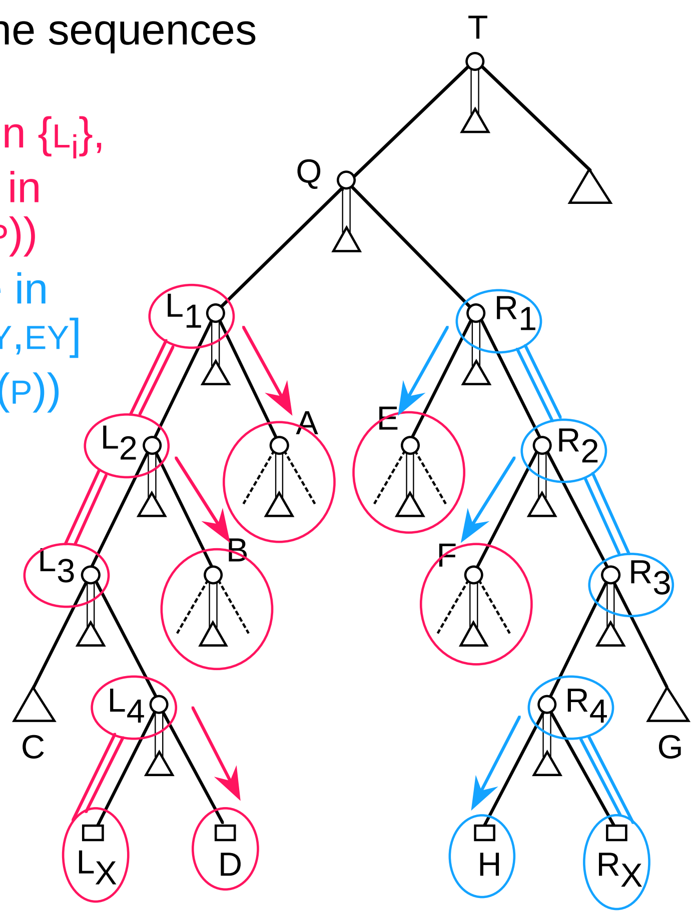
   - if P and RIGHT(P) are in {R_i}, then look for [BY,EY] in RANGE_TREE(LEFT(P))



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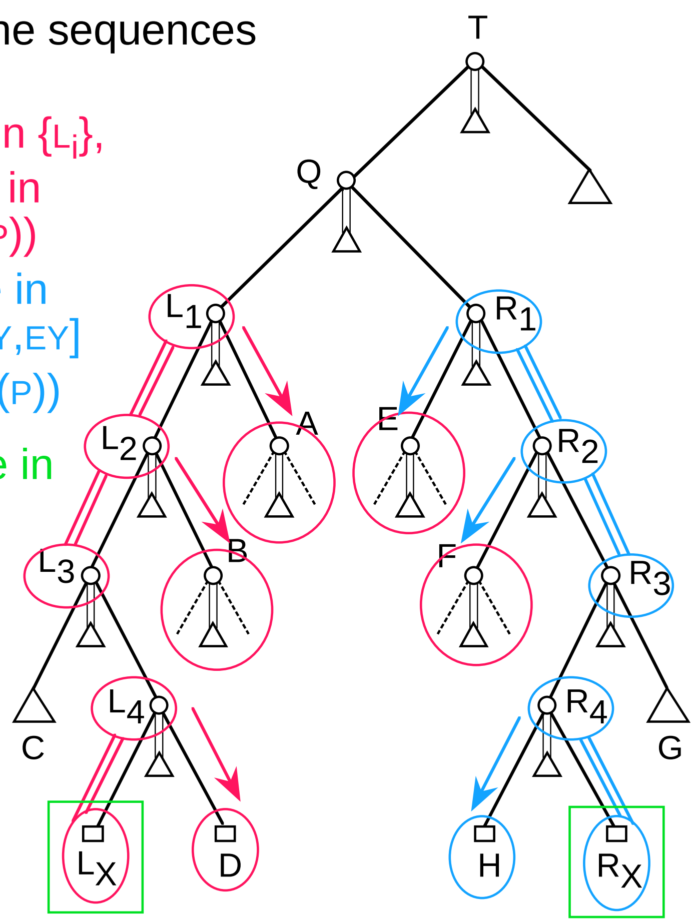
5. Check if LX and RX are in ([BX:EX],[BY:EY])



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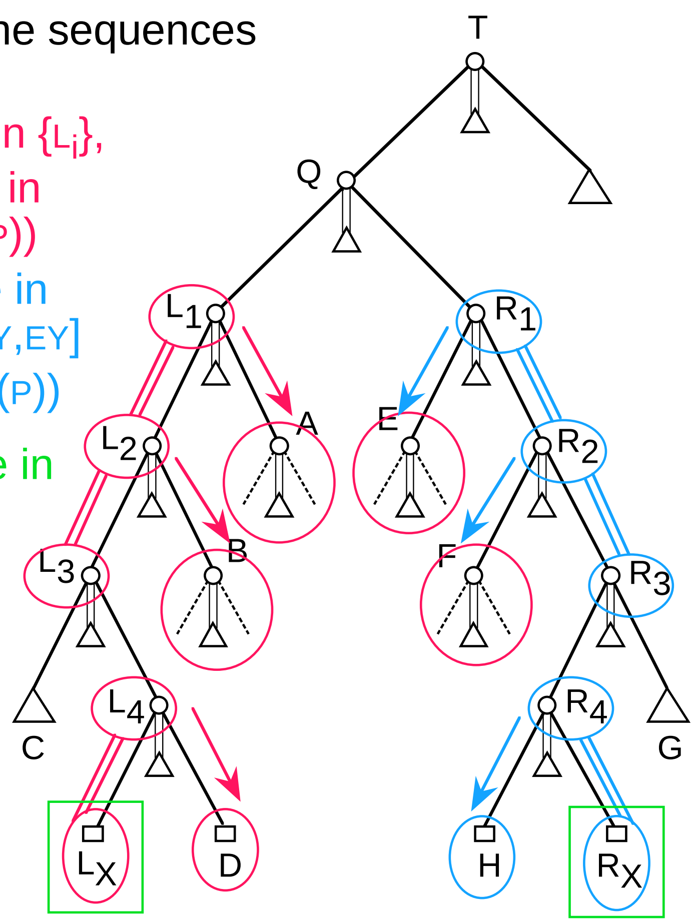
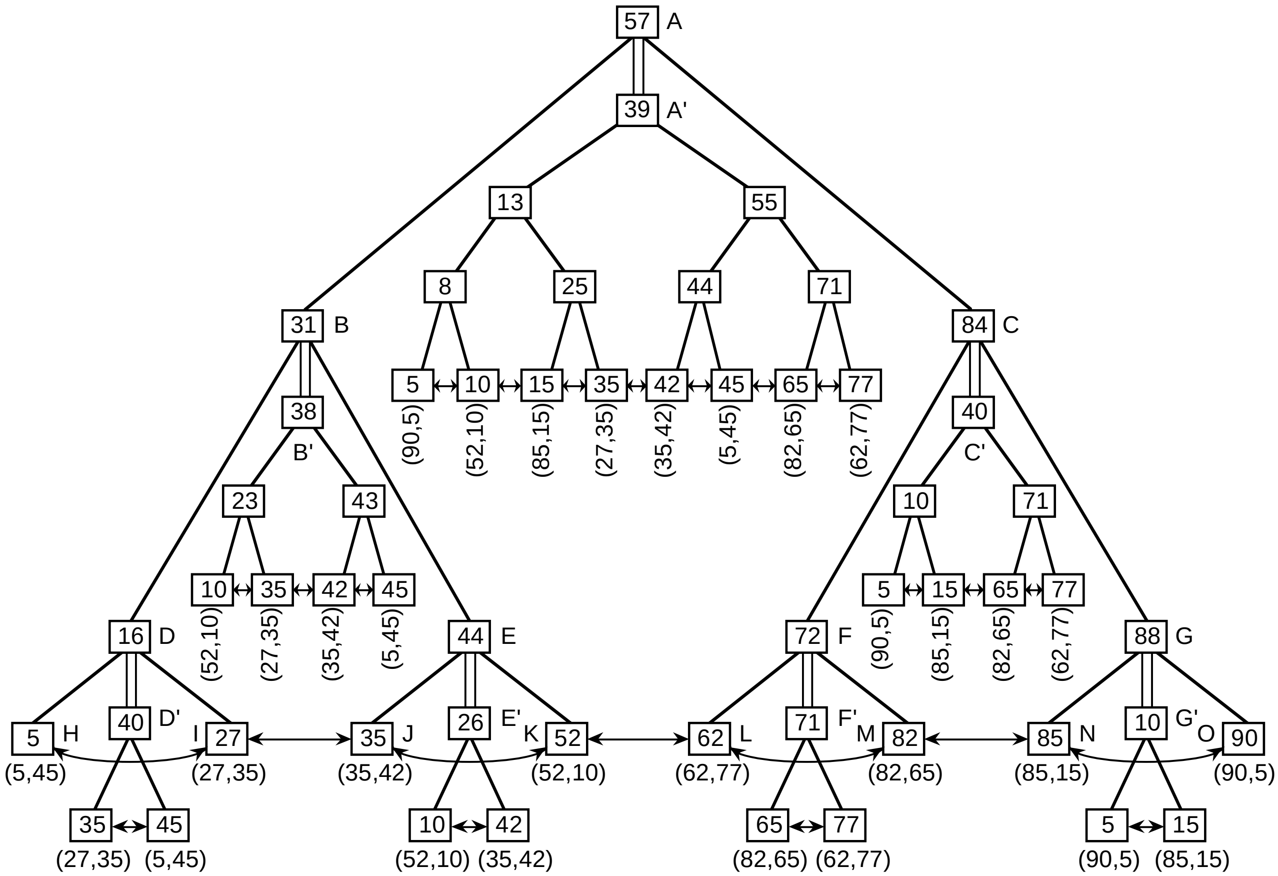


- Total $O(\log_2^2 N + F)$ time to search and $O(N \cdot \log_2 N)$ space and time to build for N points and F answers

EXAMPLE OF SEARCH IN A 2-D RANGE TREE

- Find all points in ([25:85],[8:16])



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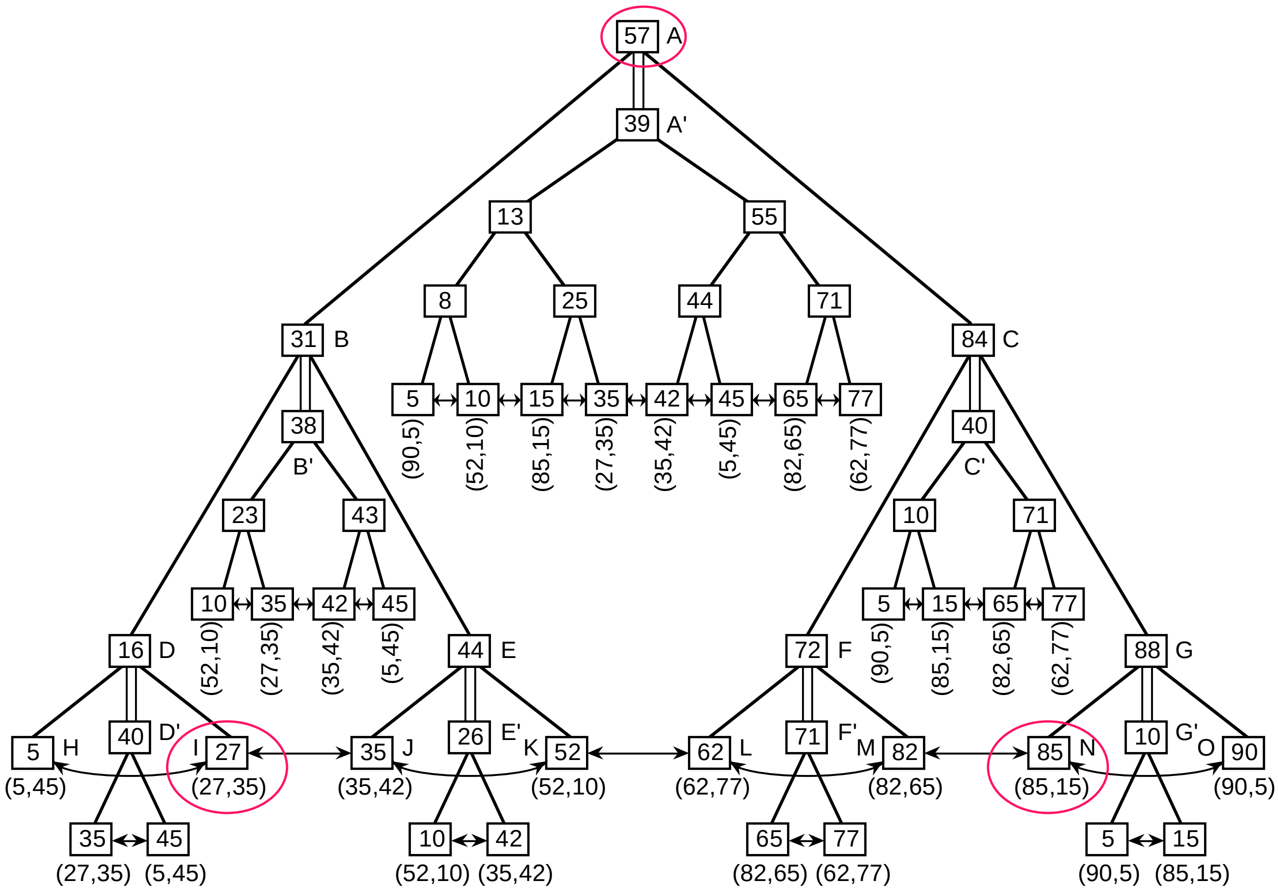

1. Find nearest common ancestor — i.e., A

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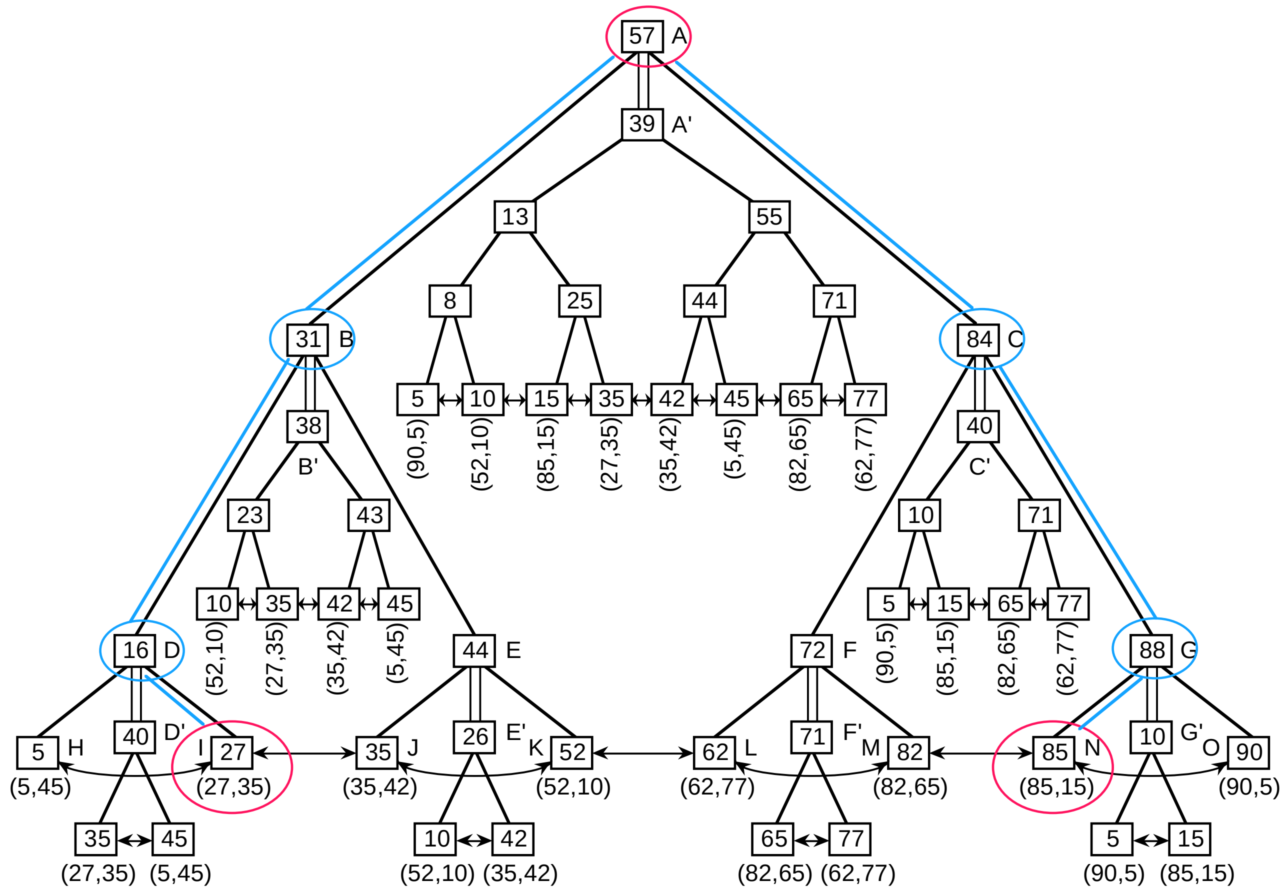

1. Find nearest common ancestor — i.e., A
2. Find paths to LX=25 and RX=85

EXAMPLE OF SEARCH IN A 2-D RANGE TREE

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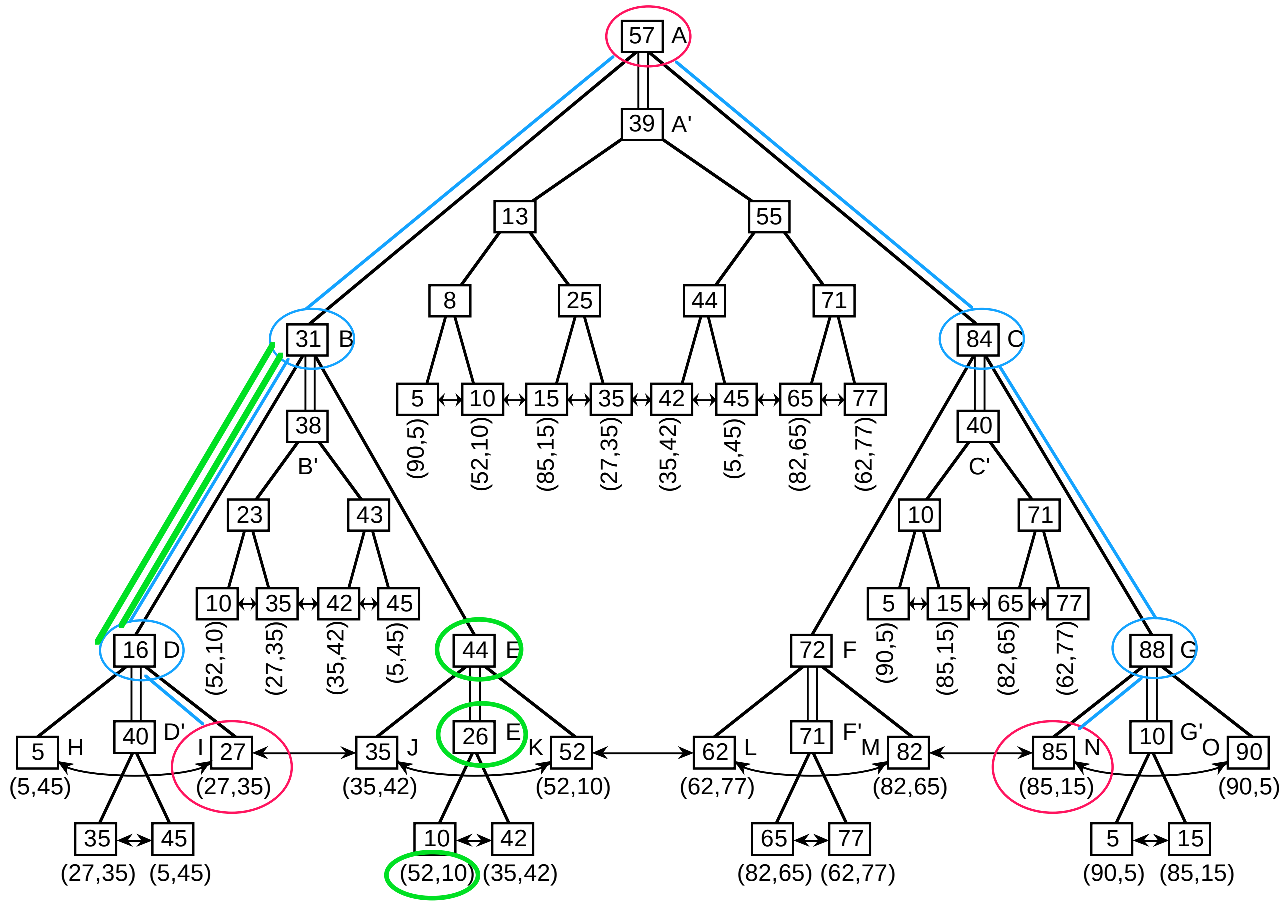

1. Find nearest common ancestor — i.e., A
2. Find paths to LX=25 and RX=85
3. Look in subtrees
   - B and B's left son D are in path, so search range tree of B's right son E and report (52,10)

5 4 3 2 1
v g z r b

rt4

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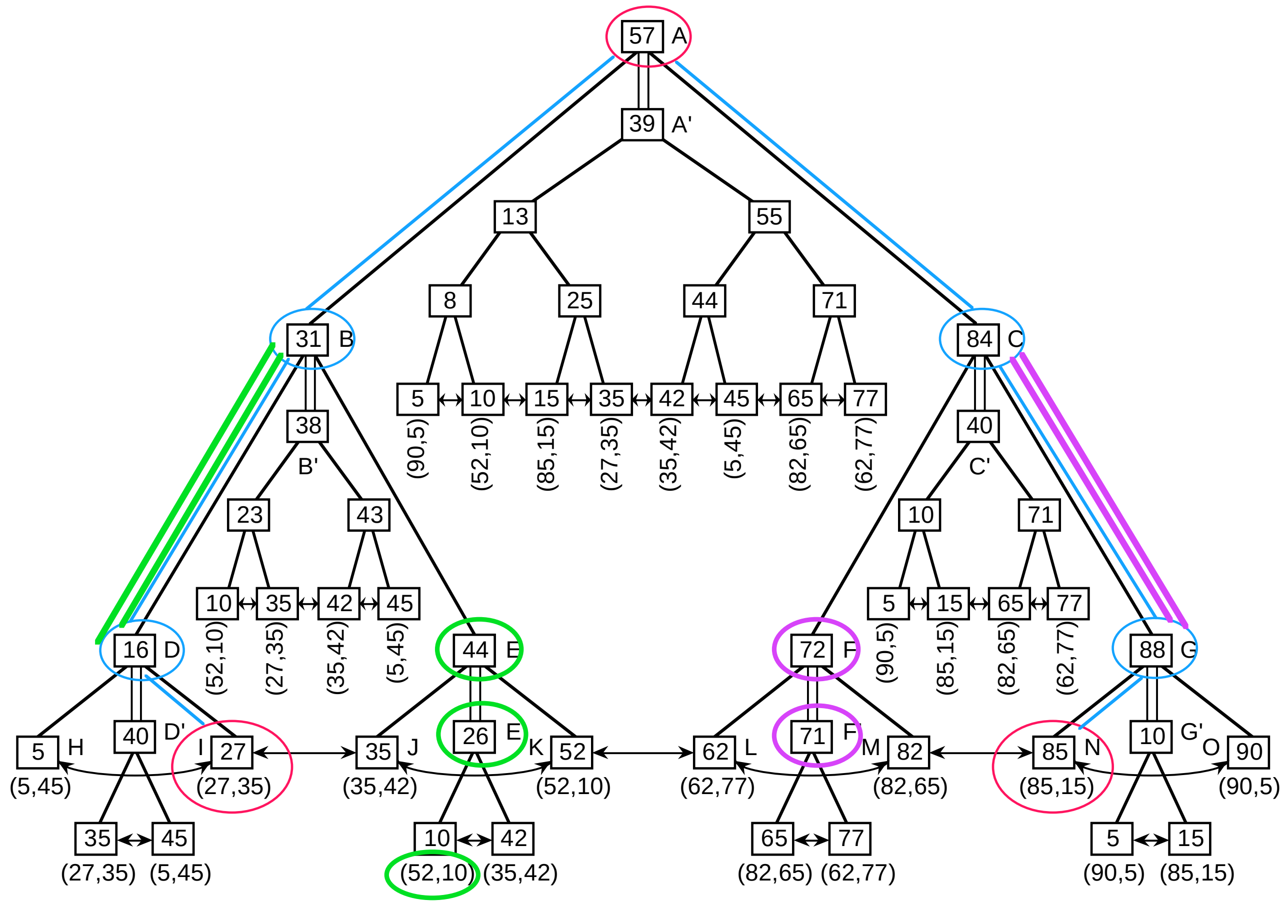


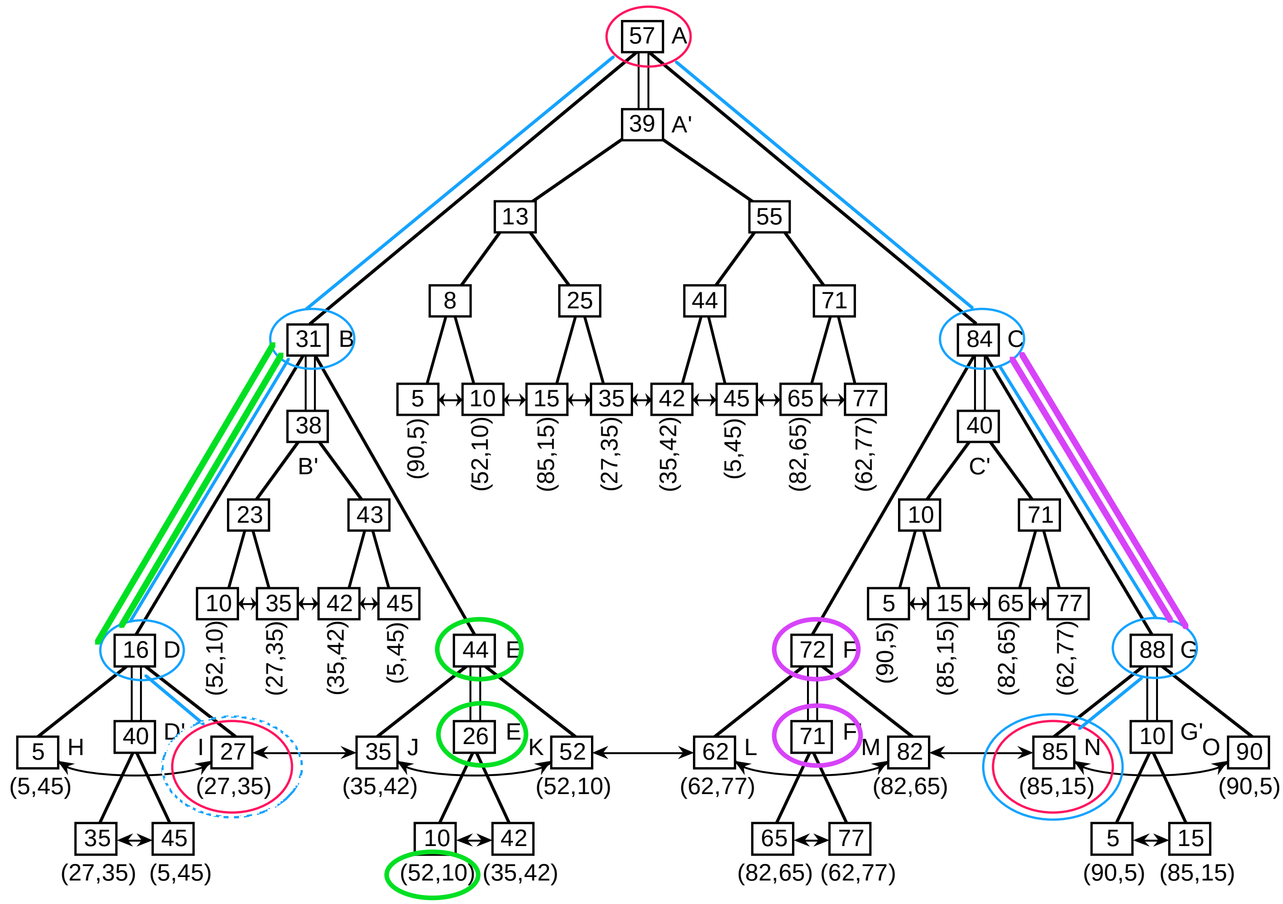
1. Find nearest common ancestor — i.e., A
2. Find paths to LX=25 and RX=85
3. Look in subtrees
   - B and B's left son D are in path, so search range tree of B's right son E and report (52,10)
   - C and C's right son G are in path, so search range tree of C's left son F and report none

6 5 4 3 2 1
z v g z r b

rt4

EXAMPLE OF SEARCH IN A 2-D RANGE TREE

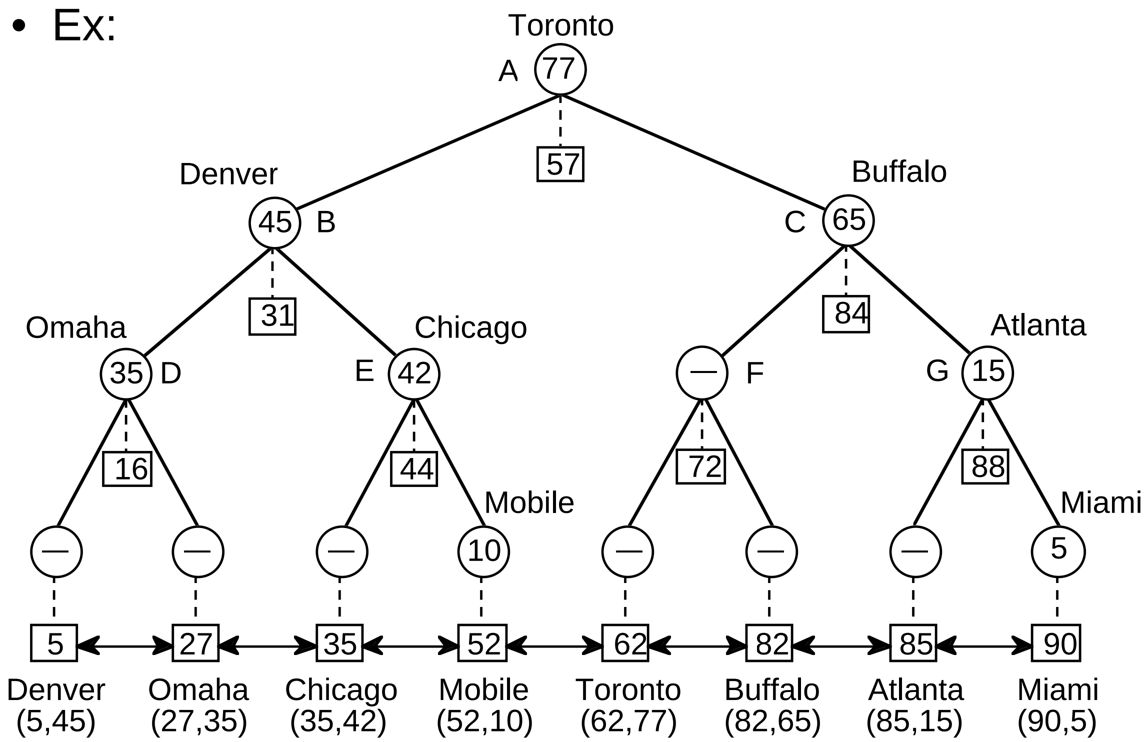
- Find all points in ([25:85],[8:16])



1. Find nearest common ancestor — i.e., A
2. Find paths to LX=25 and RX=85
3. Look in subtrees
   - B and B's left son D are in path, so search range tree of B's right son E and report (52,10)
   - C and C's right son G are in path, so search range tree of C's left son F and report none
4. Check boundaries of *x* range (i.e., (27,35) and (85,15)) and report (85,15)

PRIORITY SEARCH TREES

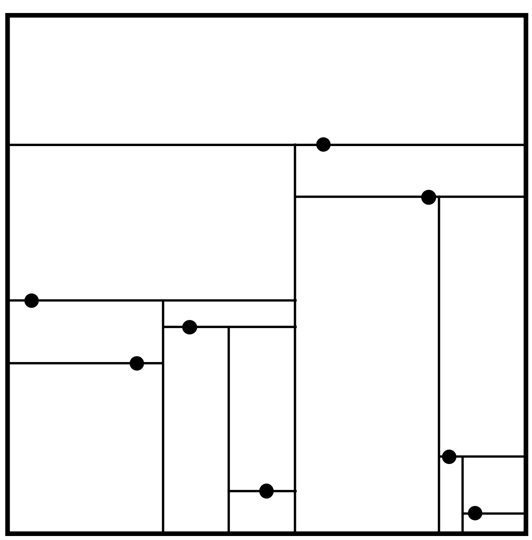
- Sort all points by their x coordinate value and store them in the leaf nodes of a balanced binary tree (i.e., a range tree)
- Starting at the root, each node contains the point in its subtree with the maximum value for its y coordinate that has not been stored at a shallower depth in the tree; if no such node exists, then node is empty
- $O(N)$ space and $O(N \cdot \log_2 N)$ time to build for N points
- Result: range tree in x and heap (i.e., priority queue) in y
- Ex:



- Good for semi-infinite ranges — i.e., ([BX:EX],[BY:∞])
- Can only perform a 2-d range query if find ([BX:EX],[BY:∞]) and discard all points (x,y) such that y > EY
- No need to link leaf nodes unless search for all points in range of x coordinate values

SEMI-INFINITE RANGE QUERY ON A PRIORITY SEARCH TREE ([BX:EX],[BY:∞])

- Procedure
  1. Descend tree looking for the nearest common ancestor of BX and EX — i.e., Q
     - associated with each examined node T is a point P
     - exit if P does not exist as all points in the subtrees have been examined and/or reported
     - exit if P_y < BY as P is point with maximum *y* coordinate value in T
     - otherwise, output P if P_x is in [BX:EX]
  2. Once Q has been found, process left and right subtrees applying the tests above to their root nodes T
     - T in left (right) subtree of Q:
       a. check if BX (EX) in LEFT(T) (RIGHT(T))
       b. yes: all points in RIGHT(T) (LEFT(T)) are in *x* range
          - check if in *y* range
          - recursively apply to LEFT(T) (RIGHT(T))
       c. no: recursively apply to RIGHT(T) (LEFT(T))
- $O(\log_2 N + F)$ time to search for *N* points and *F* answers
- Ex:



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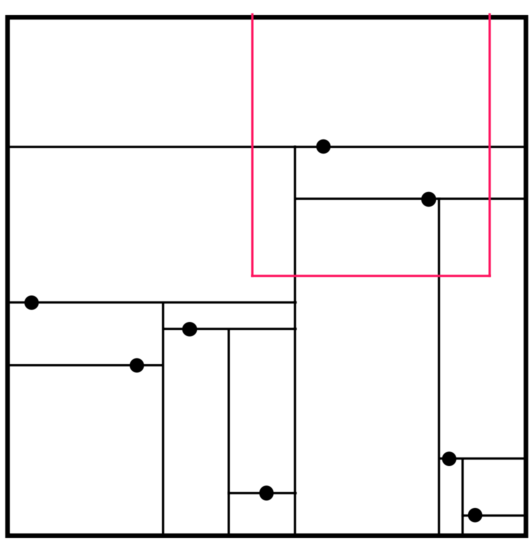
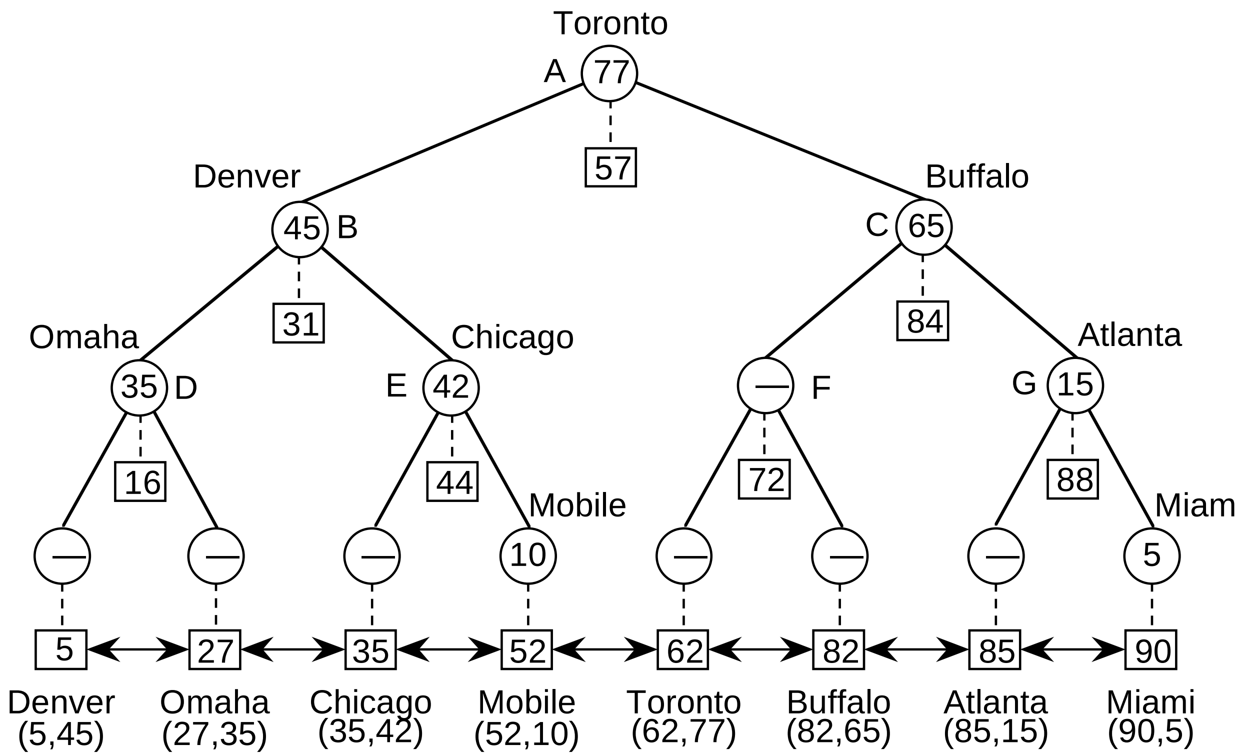
     - otherwise, output P if P_x is in [BX:EX]
  2. Once Q has been found, process left and right subtrees applying the tests above to their root nodes T
     - T in left (right) subtree of Q:
       a. check if BX (EX) in LEFT(T) (RIGHT(T))
       b. yes: all points in RIGHT(T) (LEFT(T)) are in *x* range
          - check if in *y* range
          - recursively apply to LEFT(T) (RIGHT(T))
       c. no: recursively apply to RIGHT(T) (LEFT(T))
- $O(\log_2 N + F)$ time to search for *N* points and *F* answers
- Ex: Find all points in ([35:80],[50:∞])



EXAMPLE OF A SEARCH IN A PRIORITY SEARCH TREE

- Find all points in ([35:83],[50:∞])



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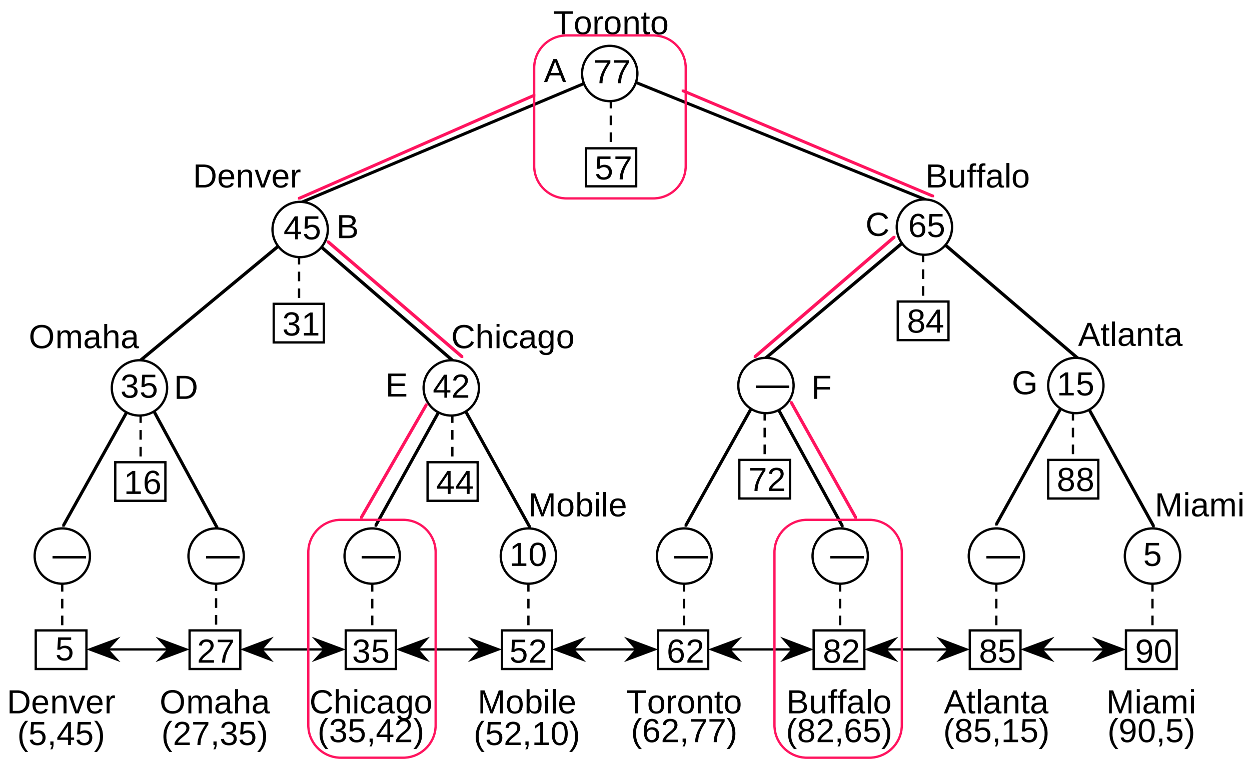
- Find all points in ([35:83],[50:∞])



1. Find nearest common ancestor — i.e., `A`
   - output `Toronto` (62,77) since 62 is in [35:80] and 77≥50

EXAMPLE OF A SEARCH IN A PRIORITY SEARCH TREE

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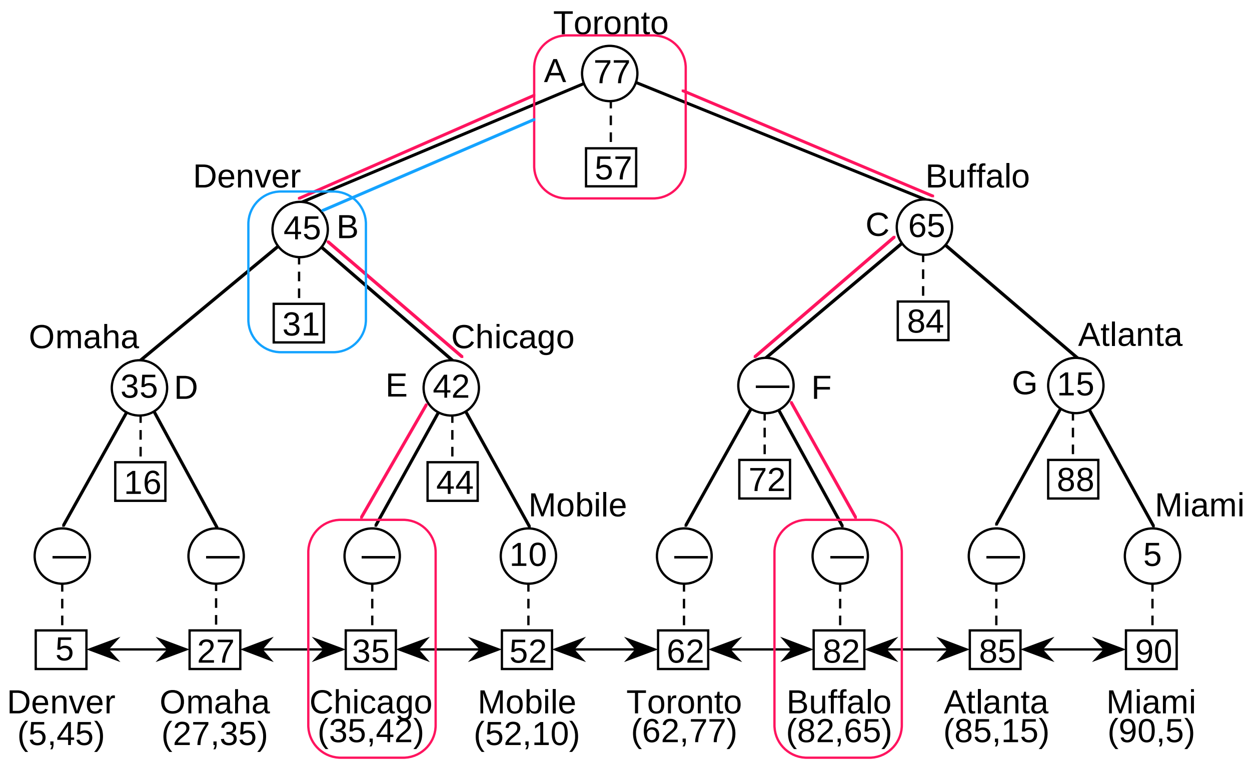

1. Find nearest common ancestor — i.e., `A`
   - output `Toronto` (62,77) since 62 is in [35:80] and 77≥50
2. Process left subtree of `A` (i.e., `B`)
   - cease processing as 45<50

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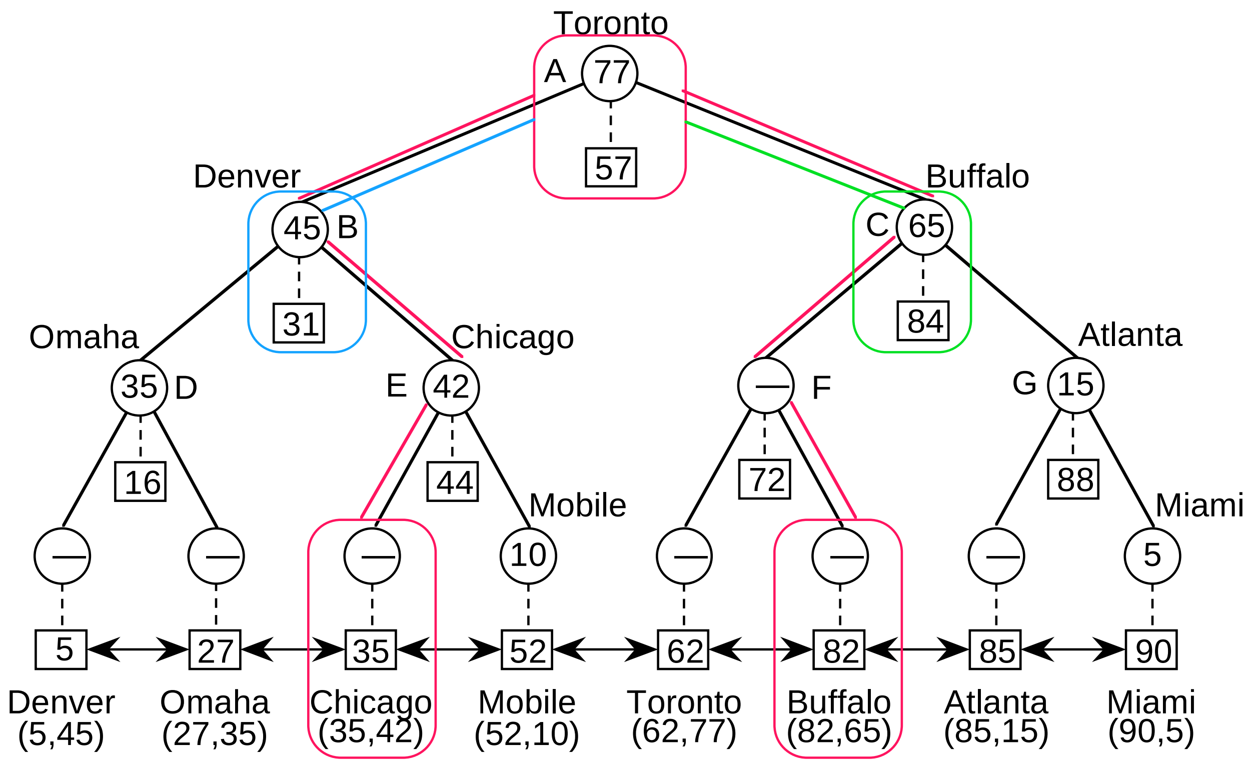

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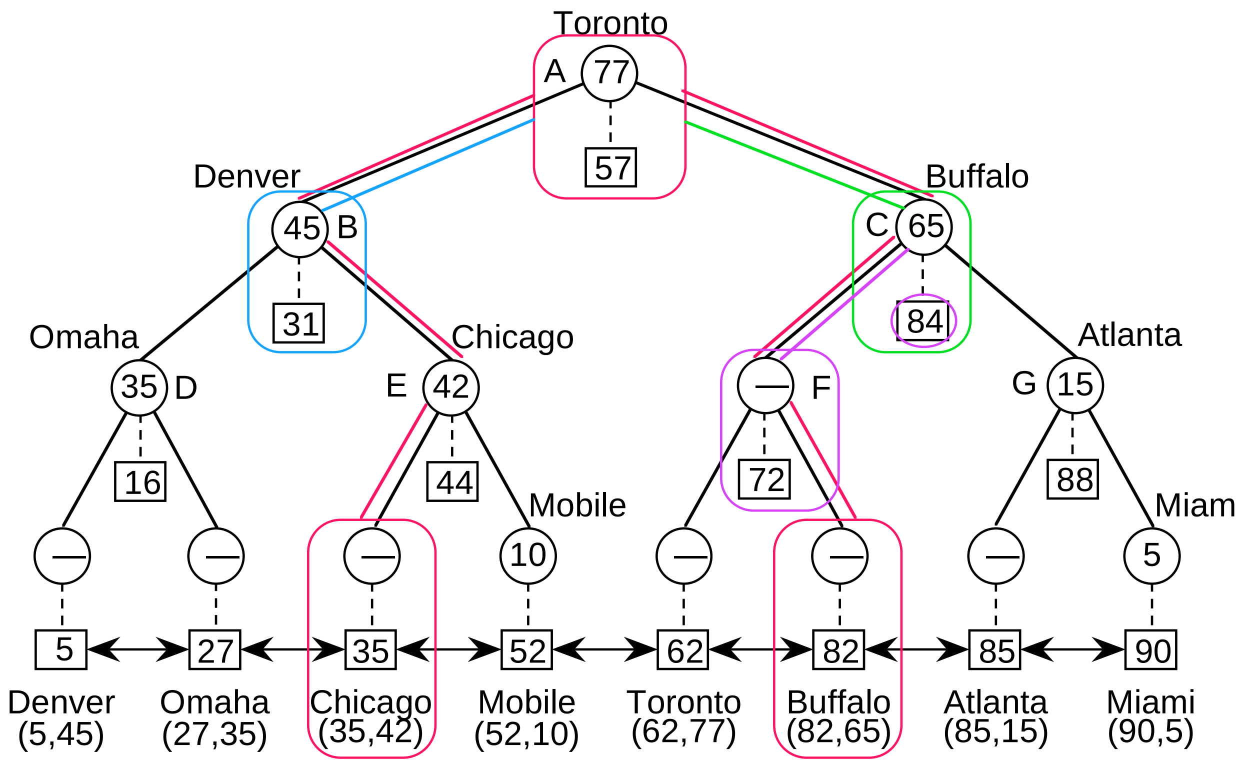
2. Process left subtree of `A` (i.e., `B`)
   - cease processing as 45<50
3. Process right subtree of `A` (i.e., `C`)
   - output (82,65) as 65 ≥ 50 and 82 is in [35:83]

EXAMPLE OF A SEARCH IN A PRIORITY SEARCH TREE

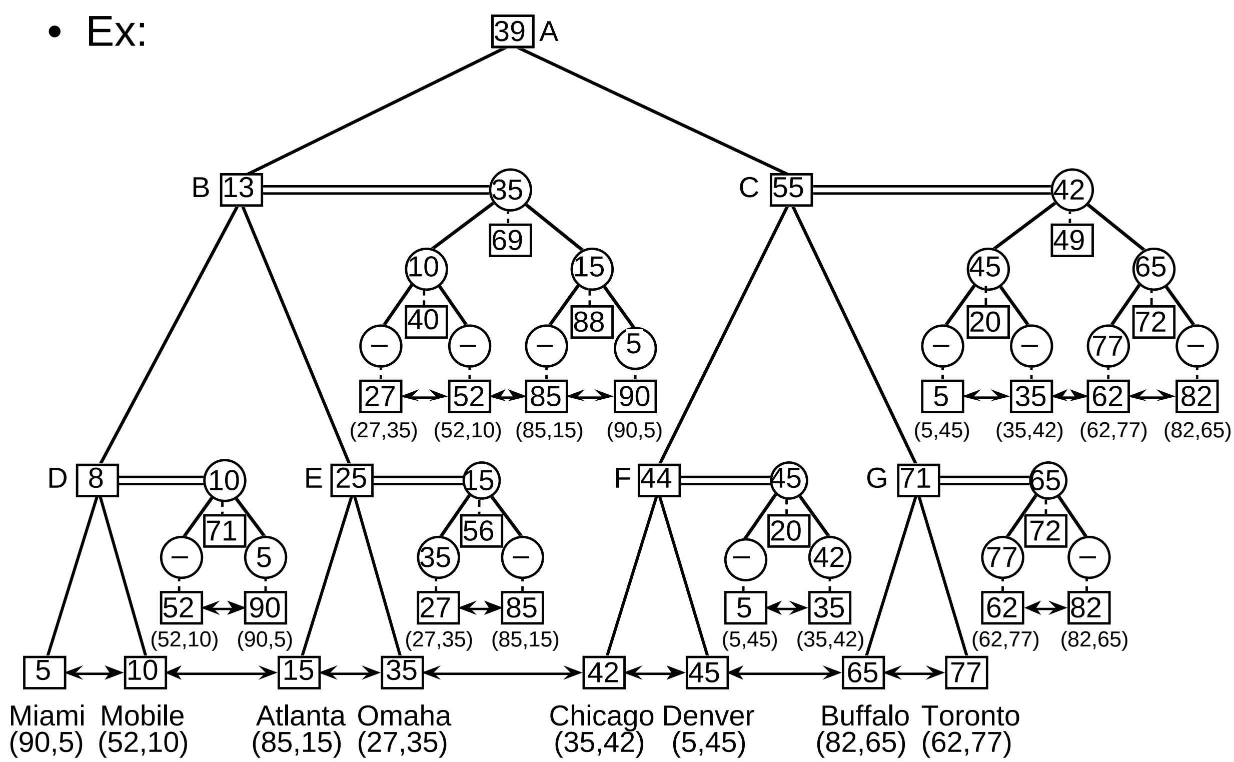
- Find all points in ([35:83],[50:∞])



1. Find nearest common ancestor — i.e., A
   - output Toronto (62,77) since 62 is in [35:80] and 77≥50
2. Process left subtree of A (i.e., B)
   - cease processing as 45<50
3. Process right subtree of A (i.e., C)
   - output (82,65) as 65 ≥ 50 and 82 is in [35:83]
4. Examine midrange value of C which is 84 and descend left subtree of C (i.e., F)
   - cease processing since no point is associated with F meaning all nodes in the subtree have been examined

RANGE PRIORITY TREES

- Variation on priority search tree
- Inverse priority search tree: heap node stores point with minimum *y* coordinate value that has not been stored in a shallower depth in the tree (instead of maximum)
- Structure
  1. sort all points by their *y* coordinate value and store in leaf of a balanced binary tree such as range tree (single lines)
     - no need to link leaf nodes unless search for all points in range of *x* coordinate values
  2. nonleaf node left sons of their father contains a priority search tree of points in subtree (double lines)
  3. nonleaf node right sons of their father contains an inverse priority search tree of points in subtree (double lines)
- $O(N \cdot \log_2 N)$ space and time to build for N points
- Ex:

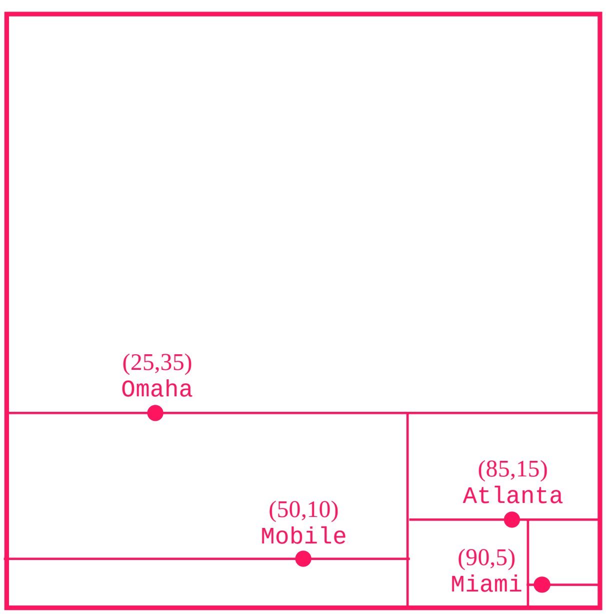


SEARCHING A RANGE PRIORITY TREE ([BX:EX],[BY:EY])

- Procedure
  1. find nearest common ancestor of BY and EY — i.e., Q

SEARCHING A RANGE PRIORITY TREE ([BX:EX],[BY:EY])

- Procedure
  1. find nearest common ancestor of BY and EY — i.e., Q
  2. all points in LEFT(Q) have *y* coordinate values <EY
     - want to retrieve just the ones ≥BY
     - find them with ([BX:EX],[BY:∞]) on priority tree of LEFT(Q)
     - priority tree is good for retrieving all points with a specific lower bound as it stores an upper bound and hence irrelevant values can be easily pruned



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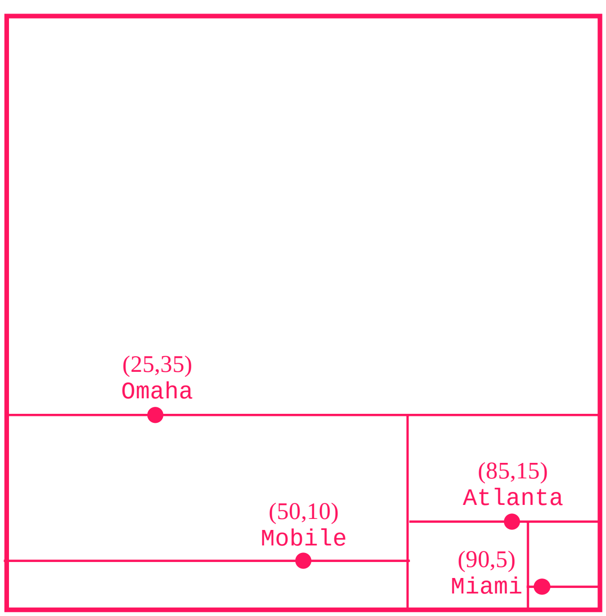
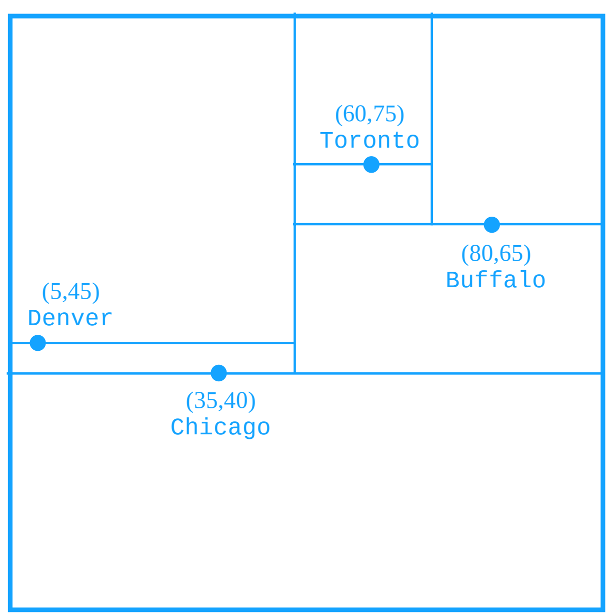
3. all points in RIGHT(Q) have *y* coordinate values >BY
   - want to retrieve just the ones ≤EY
   - find them with ([BX:EX],[–∞:EY]) on the inverse priority tree of RIGHT(Q)
   - inverse priority tree is good for retrieving all points with a specific upper bound as it stores a lower bound and hence irrelevant values can be easily pruned





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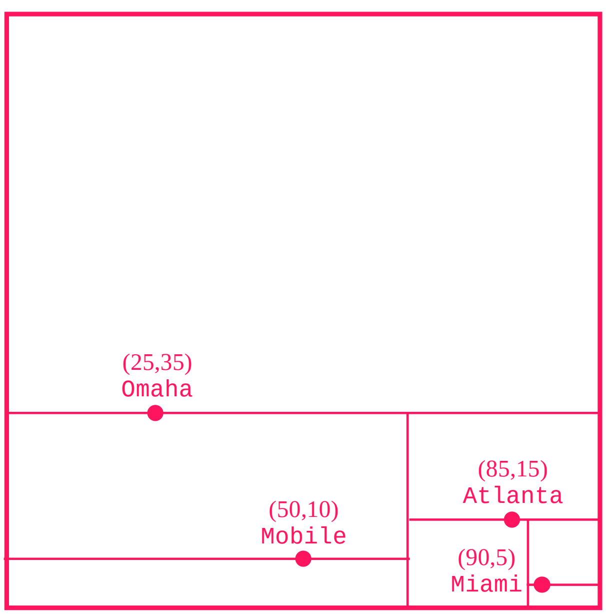
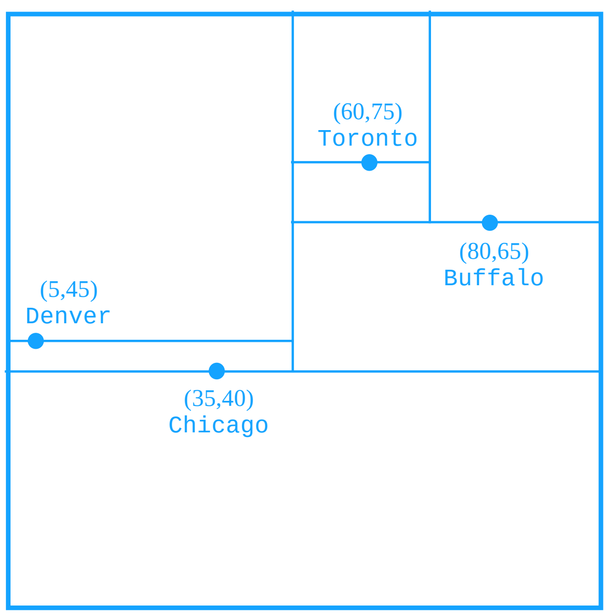
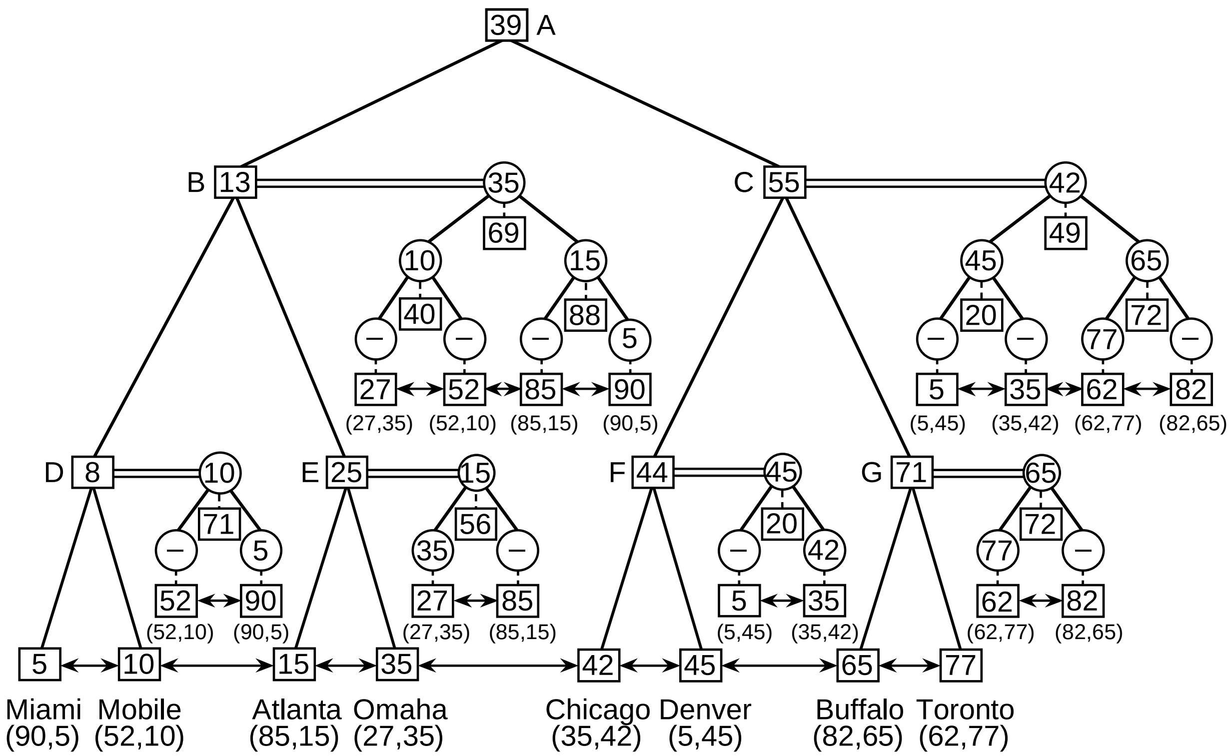
- $O(\log_2 N + F)$ time to search for N points and F answers





EXAMPLE OF A SEARCH IN A RANGE PRIORITY TREE

- Find all points in ([25:60],[15:45])



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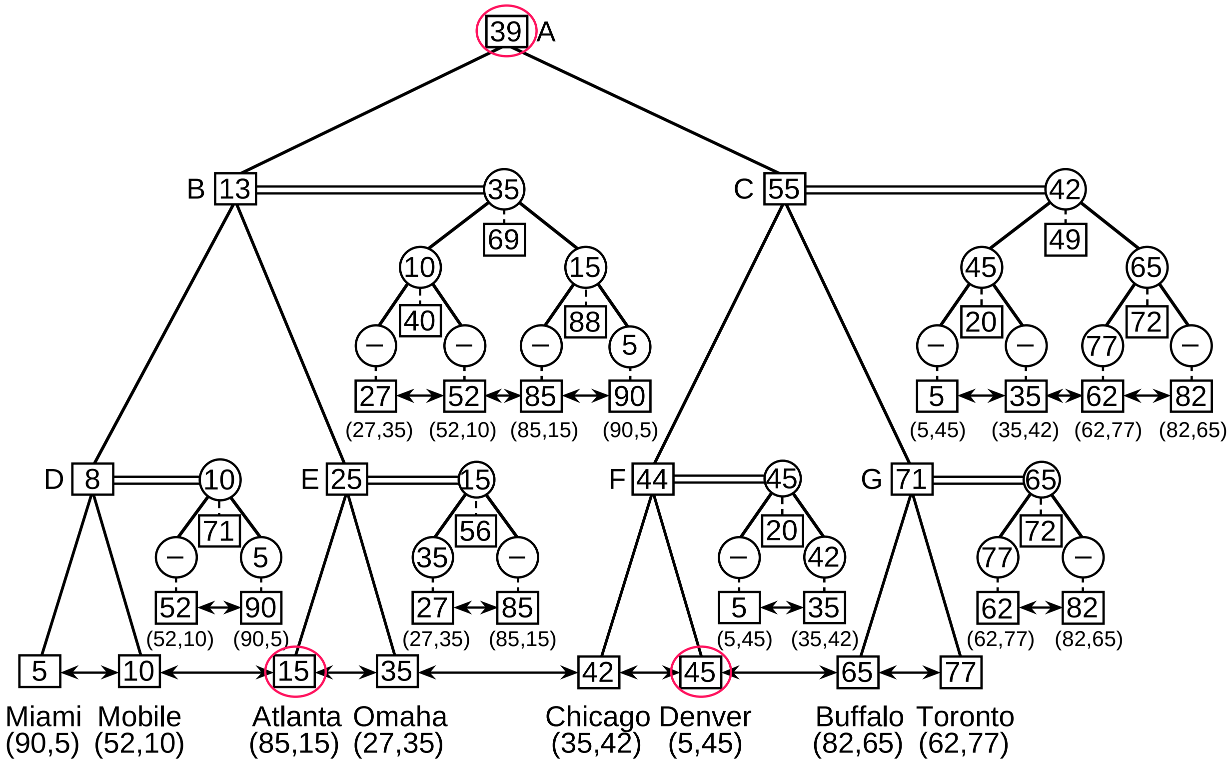

1. Find nearest common ancestor of 15 and 45 — i.e., A

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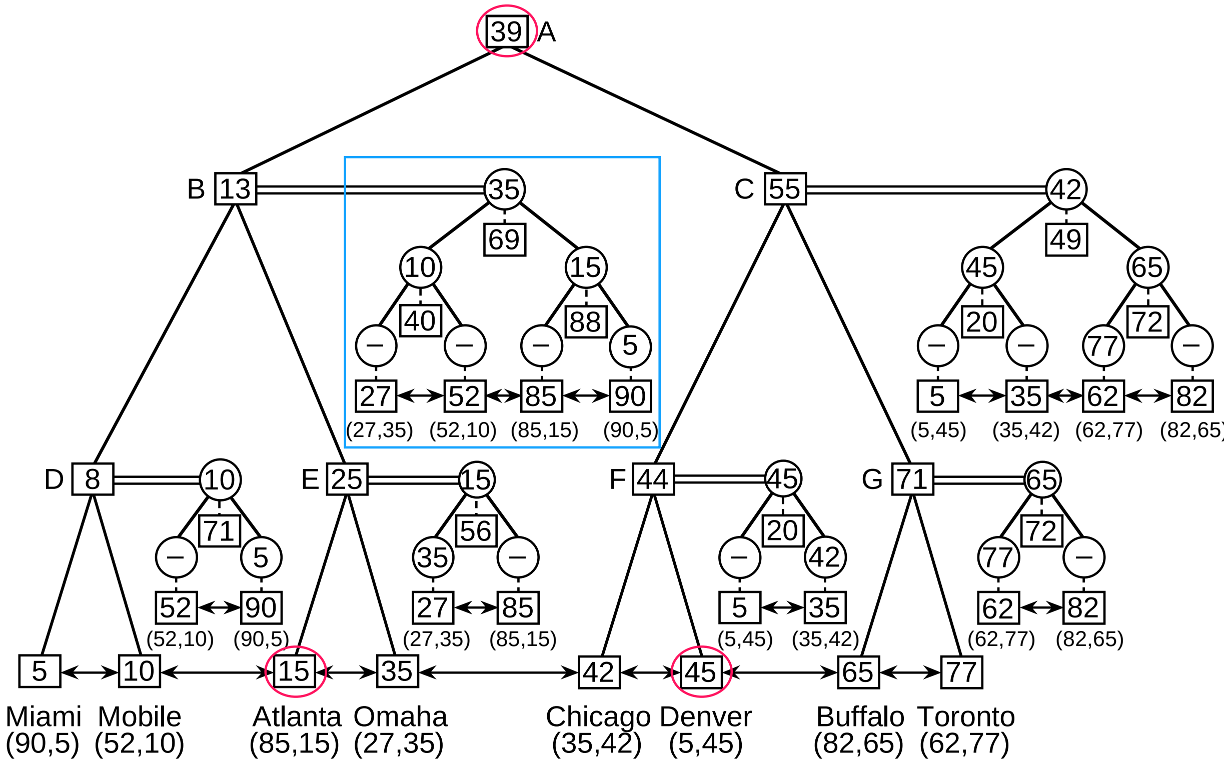

1. Find nearest common ancestor of 15 and 45 — i.e., A
2. Search for ([25:60],[15:∞]) in priority tree hanging from left son of A — i.e., B (all with *y*≤45 since a range tree in *y* and in left subtree of a node with *y* midrange value of 39)

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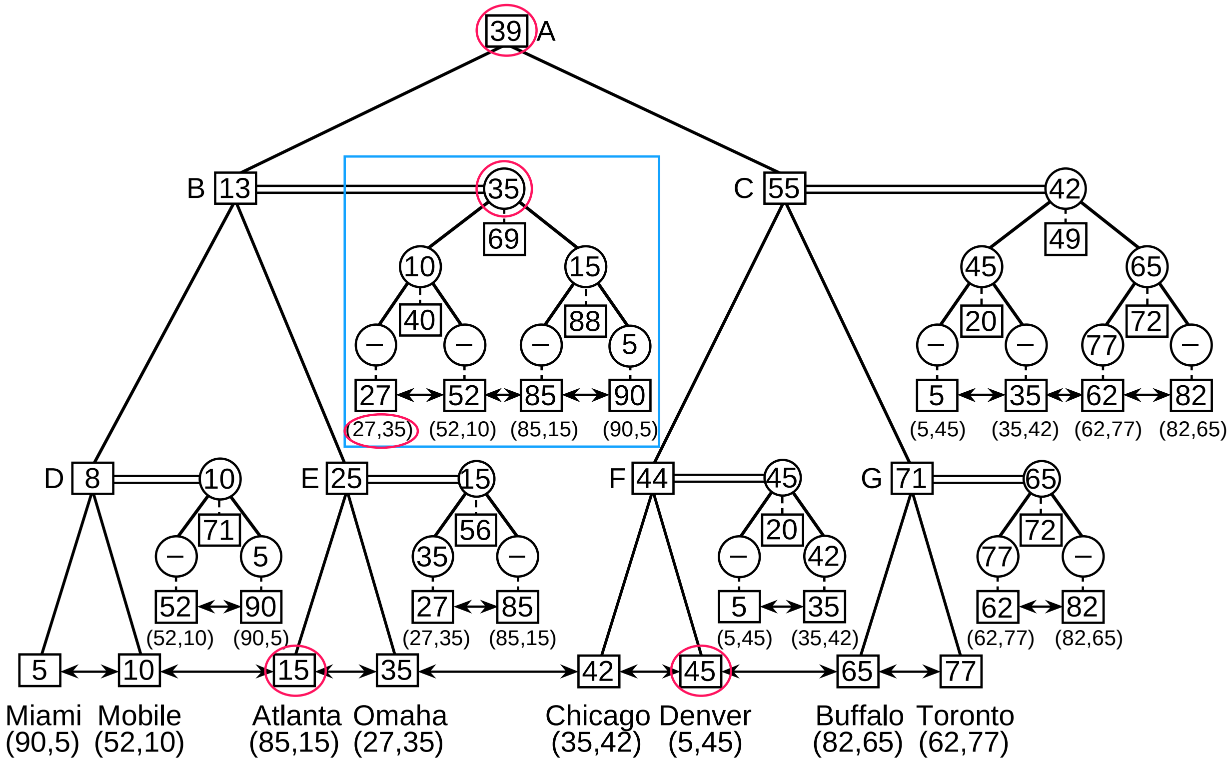
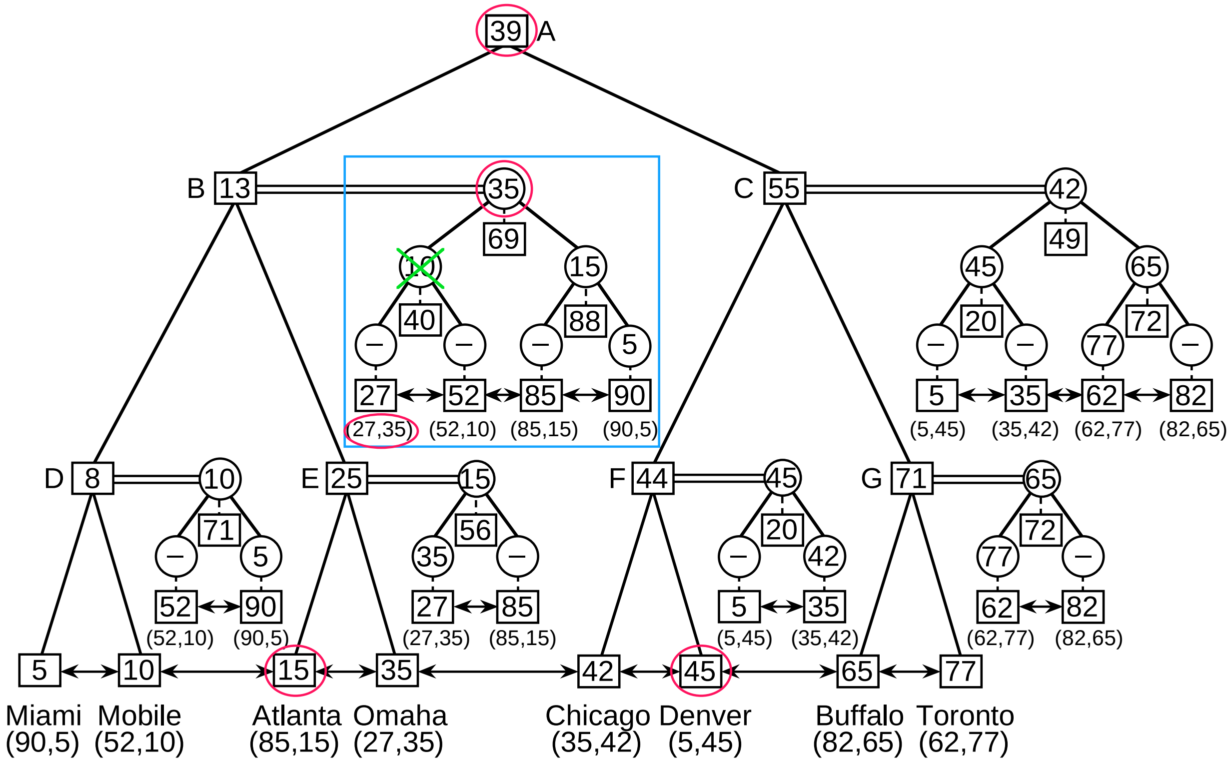


1. Find nearest common ancestor of 15 and 45 — i.e., A
2. Search for ([25:60],[15:∞]) in priority tree hanging from left son of A — i.e., B (all with $y \leq 45$ since a range tree in y and in left subtree of a node with y midrange value of 39)
   - output (27,35) as in range

EXAMPLE OF A SEARCH IN A RANGE PRIORITY TREE

- Find all points in ([25:60],[15:45])



1. Find nearest common ancestor of 15 and 45 — i.e., A
2. Search for ([25:60],[15:∞]) in priority tree hanging from left son of A — i.e., B (all with $y \leq 45$ since a range tree in y and in left subtree of a node with y midrange value of 39)
   - output (27,35) as in range
   - reject left subtree as 10 < lower limit of y range

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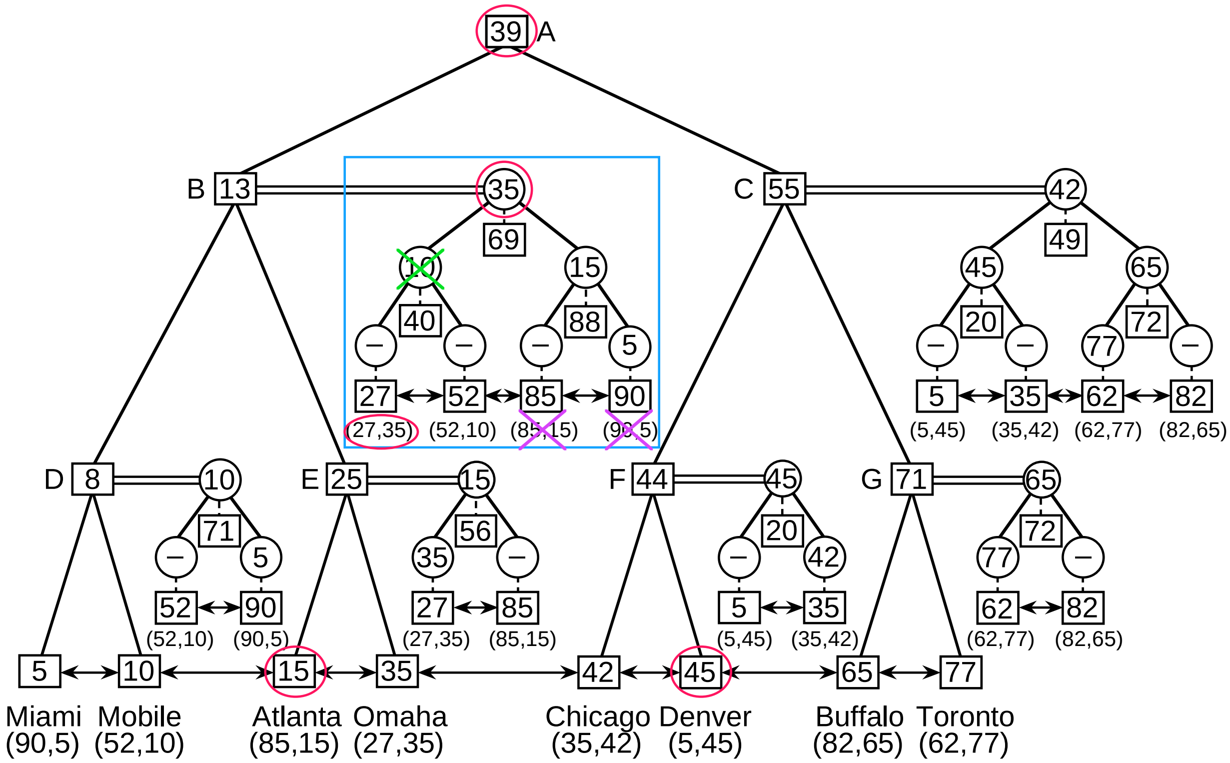

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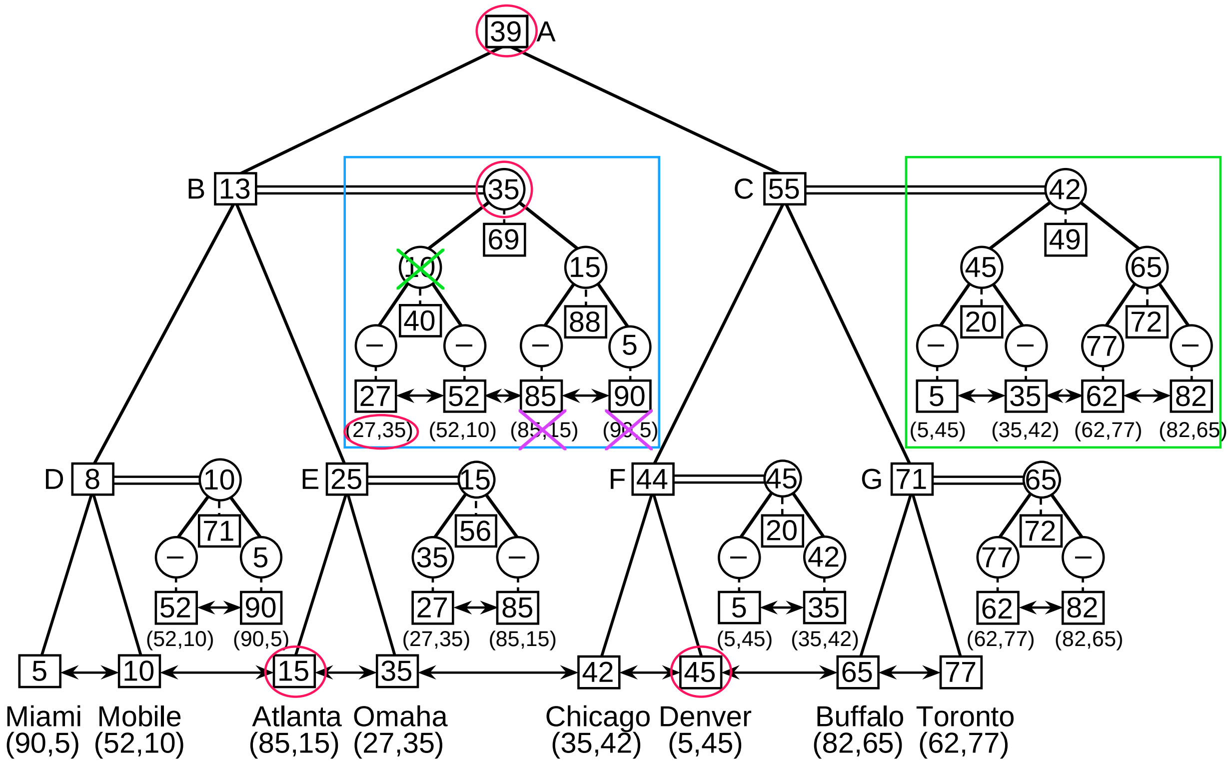

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   - output (27,35) as in range
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   - reject items in right subtree as out of *x* range
3. Search for ([25:60],[–∞:45]) in inverse priority tree hanging from right son of A — i.e., C (all with *y*≥15 since in right subtree of a node with *y* midrange value of 39)

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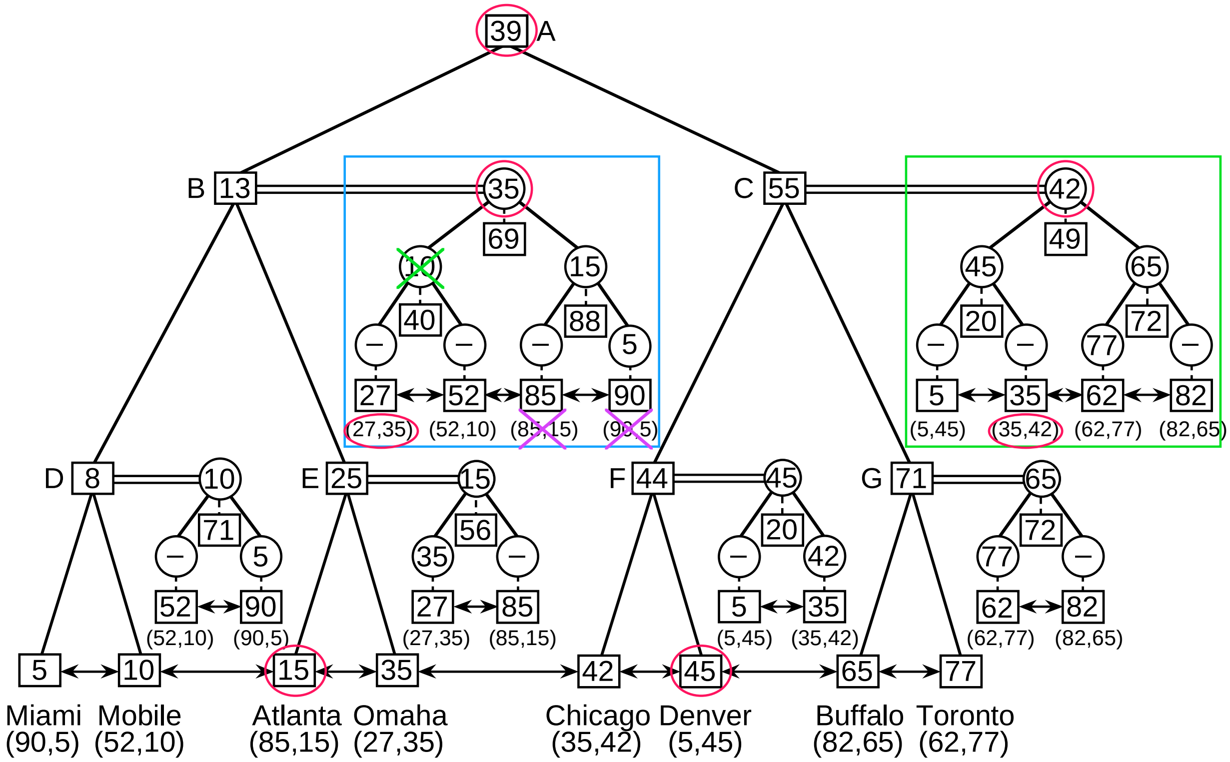

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   - output (27,35) as in range
   - reject left subtree as 10 < lower limit of *y* range
   - reject items in right subtree as out of *x* range
3. Search for ([25:60],[–∞:45]) in inverse priority tree hanging from right son of A — i.e., C (all with *y*≥15 since in right subtree of a node with *y* midrange value of 39)
   - output (35,42) as in range

EXAMPLE OF A SEARCH IN A RANGE PRIORITY TREE

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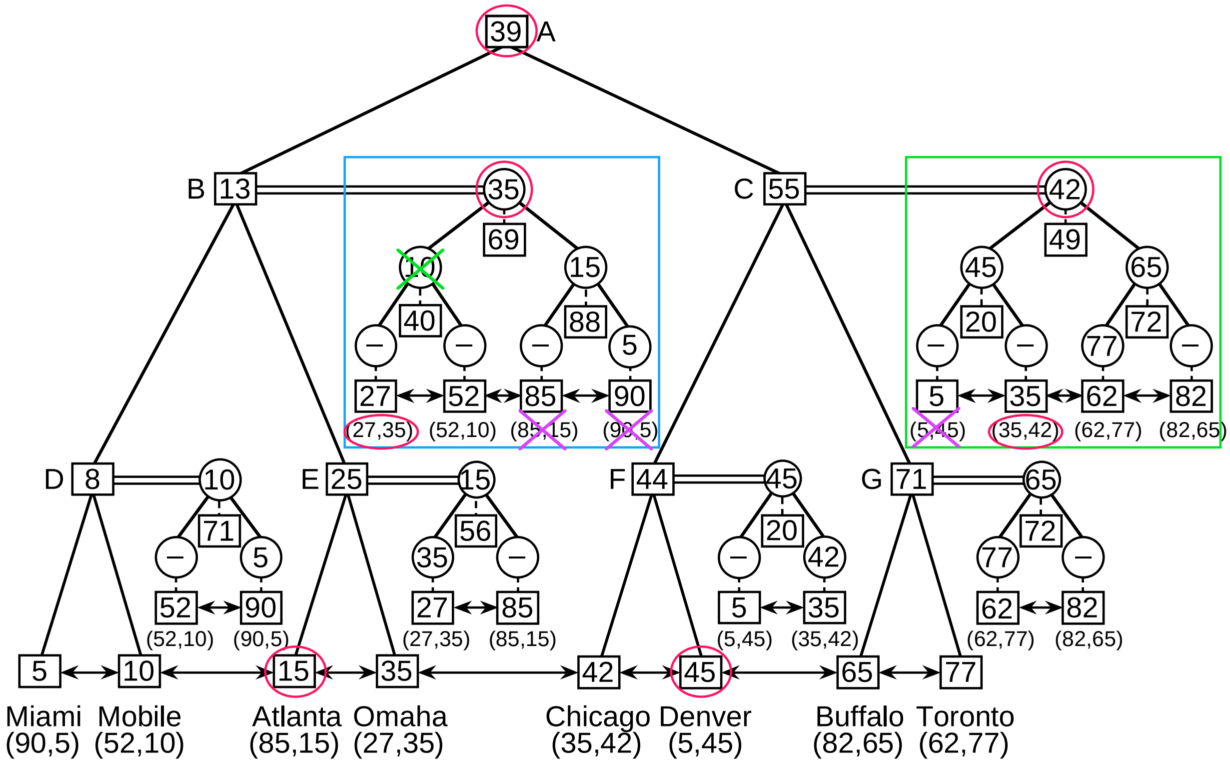

1. Find nearest common ancestor of 15 and 45 — i.e., A

2. Search for ([25:60],[15:∞]) in priority tree hanging from left son of A — i.e., B (all with *y*≤45 since a range tree in *y* and in left subtree of a node with *y* midrange value of 39)
   - output (27,35) as in range
   - reject left subtree as 10 < lower limit of *y* range
   - reject items in right subtree as out of *x* range

3. Search for ([25:60],[–∞:45]) in inverse priority tree hanging from right son of A — i.e., C (all with *y*≥15 since in right subtree of a node with *y* midrange value of 39)
   - output (35,42) as in range
   - reject unreported items in left subtree as out of *x* range

EXAMPLE OF A SEARCH IN A RANGE PRIORITY TREE

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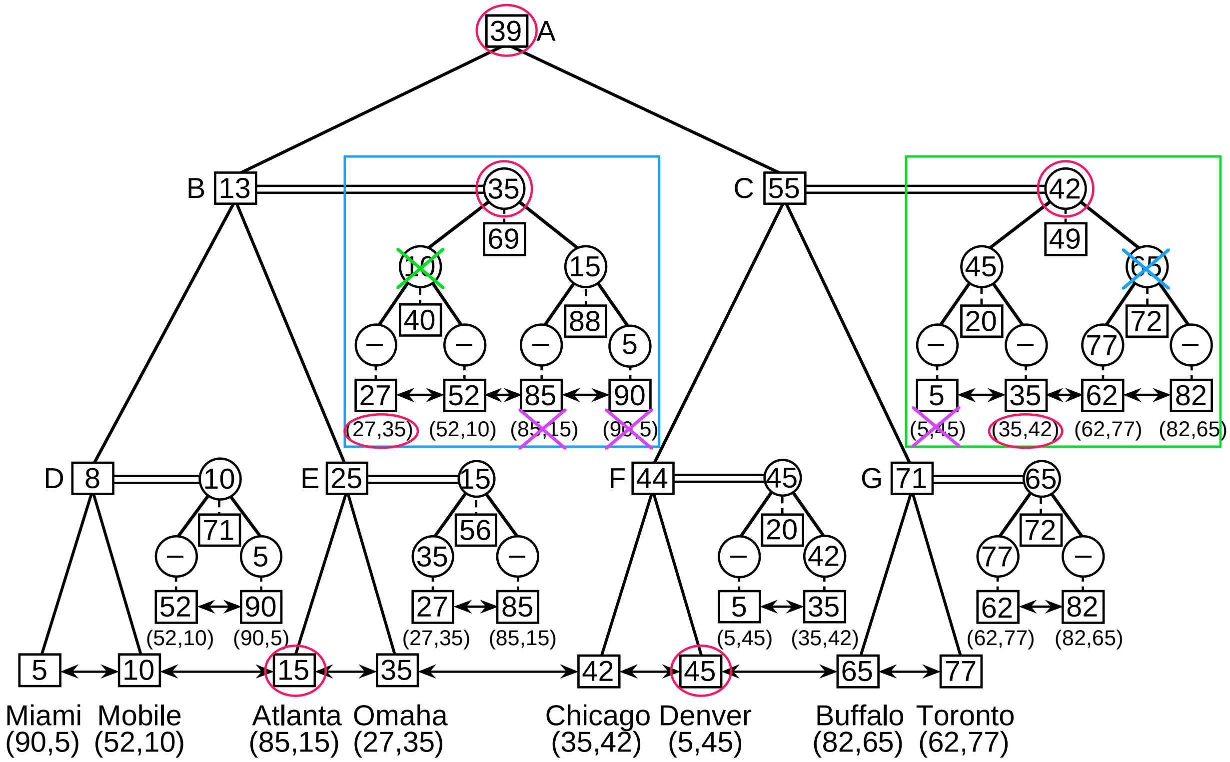

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   - output (27,35) as in range
   - reject left subtree as 10 < lower limit of y range
   - reject items in right subtree as out of x range
3. Search for ([25:60],[–∞:45]) in inverse priority tree hanging from right son of A — i.e., C (all with $y \geq 15$ since in right subtree of a node with y midrange value of 39)
   - output (35,42) as in range
   - reject unreported items in left subtree as out of x range
   - reject right subtree as 65 > upper limit of y range