### Recap: Retroactive Data Structures

#### Operations

<table>
<thead>
<tr>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INSERT</strong>*(t, operation)**: insert operation at time <em>t</em></td>
</tr>
<tr>
<td><strong>DELETE</strong>(t): delete operation at time <em>t</em></td>
</tr>
<tr>
<td><strong>QUERY</strong>(t, query): ask query at time <em>t</em></td>
</tr>
</tbody>
</table>

- for a priority queue updates are
  - insert
  - delete-min

- time is integer \( \square \) for simplicity otherwise use order-maintenance data structure

#### Definition: Partial Retroactivity

QUERY is only allowed for \( t = \infty \) \( \square \) now

#### Definition: Full Retroactivity

QUERY is allowed at any time \( t \)

#### Definition: Nonoblivious Retroactivity

INSERT, DELETE, and QUERY at any time \( t \) but also identify changed QUERY results

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<table>
<thead>
<tr>
<th>Time (t)</th>
<th>Operation</th>
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<th>Operation</th>
<th>Time (t)</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>insert(7)</td>
<td>1</td>
<td>insert(2)</td>
<td>2</td>
<td>insert(3)</td>
<td>3</td>
<td>del-min</td>
</tr>
<tr>
<td>4</td>
<td>del-min</td>
<td>5</td>
<td>queries</td>
<td>now</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Motivation: Query Set of Points

- given set of points $P = \{p_1, \ldots, p_n\}$ with $p_i = (x_i, y_i)$
- find all points in $[x, y] \times [x', y']$
- higher dimensions are possible

- think about database queries
- each dimension is a property
- searching for objects fulfilling all properties of range
consider 1-dimensional problem
range is \([x..x']\)
points \(P = \{x_1, \ldots, x_n\}\) are just numbers

build BBST where each leaf contains a point
inner node \(v\) store splitting value \(x_v\)

query for both \(x\) and \(x'\)
find leaves \(b\) and \(e\) for \(x\) and \(x'\)
let node \(v\) be node where paths to leaves split
report all leaves between \(b\) and \(e\)
1-Dimensional Range Searching (2/2)

Lemma: 1-Dimensional Range Searching

Let $P$ be a set of $n$ 1-dimensional points. $P$ can be stored in a BBST that requires $O(n)$ words space, can be constructed in $O(n \log n)$ time, and can answer range searching queries in $O(\log n + occ)$ time.

Proof (Sketch Time)

- Reporting all children in a subtree requires $O(occ)$ time.
- BBST has depth $O(\log n)$.
- Search paths starting at $v$ have length $O(\log n)$.
- Report all subtrees to the right of the left path.
- Report all subtrees to the left of the right path.
Important

- for now: assume now two points have the same $x$- or $y$-coordinate

- generalize 1-dimensional idea

1-dimensional
- split number of points in half at each node
- points consist of one value

2-dimensional
- points consist of two values
- split number of points in half w.r.t. one value
- switch between values depending on depth
Kd-Trees (1/4)

- considering the 2-dimensional case
- each inner node at an even depth
  - splits the leaves in its subtree in half
  - using the $x$-coordinate
- each inner node at an odd depth
  - splits the leaves in its subtree in half
  - using the $y$-coordinate
- until each region contains a single point
- each leaf represents a point

- splitting in linear time is complicated
- better presort based on $x$- and $y$-coordinate
- inner nodes store splitter (line)
Kd-Trees (2/4)

Lemma: Kd-Tree Construction
A kd-tree for a set of $n$ points requires $O(n)$ words space and can be constructed in $O(n \log n)$ time.

Proof (Sketch: Space)
- there are $O(n)$ leaves
- there are $O(n)$ inner nodes
- a binary tree requires $O(1)$ words per node
- $O(n)$ words total space

Proof (Sketch: Time)
- finding the splitter is easy due to presorted points
- splitting requires $T(n)$ time with
  \[
  T(n) = \begin{cases} 
  O(1) & n = 1 \\
  O(n) + 2T(\lceil n/2 \rceil) & n > 1 
  \end{cases}
  \]
- results in $O(n \log n)$ running time
- dominates presorting
Kd-Trees (3/4)

- use splitter depending on depth to identify paths through tree
- if a region is fully contained in query: report region
- if a region is intersected by query: check if point has to be reported

- precomputation of requires note necessary
- current region can be computed during query
- using splitters

- example on the board
Lemma: Kd-Tree Query

A query with an axis-parallel rectangle in a Kd-tree storing \( n \) points in the plane can be performed in \( O(\sqrt{n} + \text{occ}) \) time.

Proof (Sketch)

- \( O(\text{occ}) \) time necessary to report points
- look at number of regions intersected by any vertical line
- upper bound for the regions intersected by query (for left and right edge of rectangle)
- upper bound for top and bottom edges are the same

Proof (Sketch, cnt.)

- for vertical lines consider every inner node at odd depth
- starting at root’s children
- can intersect two regions
- number of nodes is \([n/4]\) halved at each level
- number of intersected regions is \( Q(n) \) with

\[
Q(n) = \begin{cases} 
  O(1) & n = 1 \\
  2 + 2Q(\lceil n/4 \rceil) & n > 1 
\end{cases}
\]

- results in \( Q(n) = O(\sqrt{n}) \)
- \( O(\sqrt{n} + k) \) total running time
Range Trees (1/4)

- one BBST build on the $x$-coordinates
  - same as for 1-dimensional queries
- each inner node is associated with a set of points
- build a BBST for the $y$-coordinates of associated points for each inner node
  - store points in leaves not just $y$-coordinates
  - this BBST is used for reporting
- space-query-time trade-off
- faster queries but larger
the BBST for the \( x \)-coordinates requires \( O(n) \)
words of space

how much space do the associated BBSTs require in total?

Lemma: Space Range Tree

A range tree on a set of \( n \) points in the plane requires
\( O(n \log n) \) words space

Proof (Sketch)

- BBST for \( x \)-coordinates has depth \( O(\log n) \)
- all points are represented on each depth exactly once

Proof (Sketch, cnt.)

- all associated BBSTs on each depth contain every point exactly once
- total size of all BBSTs on each depth is \( O(n) \)
- total space \( O(n \log n) \) words

how much faster is the range tree?
Range Trees (3/4)

- 2-dimensional rectangular range search reduced to two 1-dimensional range searches
- look in BBST for $x$-coordinates same as 1-dimensional case
- instead of reporting subtrees to the right/left of paths search associated BBSTs
- report results in leaves of associated BBSTs

Lemma: Rang Tree Query Time

A query with an axis-parallel rectangle in a range tree storing $n$ points requires $O(\log^2 n + \text{occ})$ time

Proof (Sketch)

- each search in an associated BBST $t$ requires $O(\log n + \text{occ}_t)$ time
- $O(\log n)$ associated BSSTs $T$ are searched as seen in 1-dimensional case
- total query time $\sum_{t \in T} O(\log n + \text{occ}_t) = O(\text{occ})$
- $\sum_{t \in T} O(\log n) = O(\log^2 n)$
- total time: $O(\log^2 n + \text{occ})$
Range Trees (4/4)

- Range trees can be generalized to higher dimensions.
- For each dimension add an additional associated BBST.
- Reporting in final BBST.
- \(d\)-dimensional queries are \(d\) 1-dimensional queries.

**Lemma: Higher Dimensions Range Tree**

A \(d\)-dimensional range tree (for \(d \geq 2\)) storing \(n\) points in the plane requires \(O(n \log^{d-1} n)\) words space and can answer queries in \(O(\log^d n + \text{occ})\) time.

**Proof (Sketch Query Time)**

- Recursive query time \(Q_d(n)\) with \(Q_2(n) = O(\log^2 n)\)
- \(Q_d(n) = O(\log n) + O(\log n) \cdot Q_{d-1}(n)\)
- Solves to \(Q_d(n) = O(\log^d n)\)
- \(O(\text{occ})\) time for reporting

**Proof (Sketch Construction Space)**

- Recursive space \(S_d(n)\) with \(S_2(n) = O(n \log n)\) words
- \(T_d(n) = O(n \log n) + O(\log n) \cdot T_{d-1}(n)\)
- Solves to \(S_d(n) = O(n \log^{d-1} n)\)
sorted sets $S_1, \ldots, S_m$

$|S_1| = n$ and $S_{i+1} \subseteq S_i$

report elements in range $[x..x']$ in $S_1, \ldots, S_m$

how much time does a naive algorithm with binary search require?

$O(m \log n + \text{occ})$ time

$O(m + \log n + \text{occ})$ time possible with fractional cascading

in addition to $S_i$ store pointers to $S_{i+1}$

for each element in $S_i$ store pointer to successor in $S_{i+1}$

possible because $S_{i+1} \subseteq S_i$
Lemma:
Given sets $S_1, \ldots, S_m$ with $|S_1| = n$ and $S_{i+1} \subseteq S_i$, find a range in all $S_i$'s using fractional cascading requires $O(m + \log n + \text{occ})$ time.

Proof (Sketch)
- Binary search on $S_1$ requires $O(\log n)$ time.
- Following pointer to $S_2$ requires $O(1)$ time.
- Scanning $S_2$ requires $O(\text{occ})$ time.
- Following pointer to $S_3$ requires $O(1)$ time.
- Repeat $m$ times.
- Total: $O(m + \log n + \text{occ})$ time.

- How to apply to range trees?
- Instead of associated BBSTs store leaf data in arrays for all nodes but root.
- Each node has associated data.
- Store two successor pointers to the associated data in the left and right child.
- Two pointers to cover all possible paths.
- This is a layered range tree.
Query Layered Range Trees

- search in BBST for $x$-coordinates remains the same
- to search $y$-coordinates first search associated BBST of root
- same as initial binary search for fractional cascading
- continue to follow pointers in associated data and scan to report queries

Proof (Sketch)

- the initial search requires $O(\log n)$ time
- the search in the associated BBST of the root requires $O(\log n)$ time
- remaining searches in associated data $a$ requires $O(1 + \text{occ}_a)$ time
- each point is reported once
- total time: $O(\log n + \text{occ})$

Lemma: Query time Layered Range Tree

A query with an axis-parallel rectangle in a layered range tree storing $n$ points in the plane can be performed in $O(\log n + \text{occ})$ time
General Sets of Points

- all solutions requires unique $x$ and $y$-coordinate combination
- big limitation for applications
- remember database motivation

- store $(x|k)$ as coordinate with $x$ being the $x$-coordinate and $k$ a unique key
- same for $y$-coordinates
- compare points using
  $(x|k) < (x'|k') \iff x < x' \text{ or } (x = x' \text{ and } k < K')$

-range queries $[x..x'] \times [y..y']$ become
  
  $[(x| - \infty)..<x'|\infty]] \times (y| - \infty)..[(y'|\infty)]$
Conclusion and Outlook

This Lecture
- orthogonal range searching

Next Lecture
- geometric data structures
- Q&A
- results of evaluation

Advanced Data Structures

- retroactive PQ
- String B-tree
- SA & LCP
- Kd- & Range Tree
- Successor
- CSA
- RMQ
- static/dynamic BV
- static/dynamic succ. trees
- range min-max tree
- succ. graphs