Advanced Data Structures

Lecture 05: Orthogonal Range Searching

Florian Kurpicz and Daniel Funke

PINGO

https://pingo.scc.kit.edu/054040

Motivation: Query Set of Points

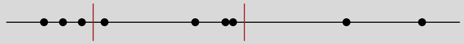
Karlsruhe Institute of Technology

- 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

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

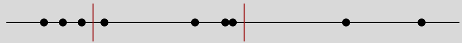


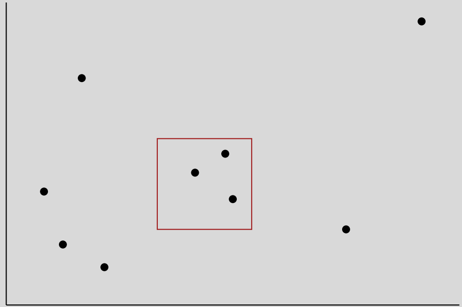
- think about database queries
- each dimension is a property
- searching for objects fulfilling all properties of range

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





1-Dimensional Range Searching (1/2)

Karlsruhe Institute of Technology

- consider 1-dimensional problem
- range is $[x..x']$
- points $P = \{x_1, \ldots, x_n\}$ are just numbers

1-Dimensional Range Searching (1/2)

- consider 1-dimensional problem
- range is $[x..x']$
- points $P = \{x_1, \dots, x_n\}$ are just numbers

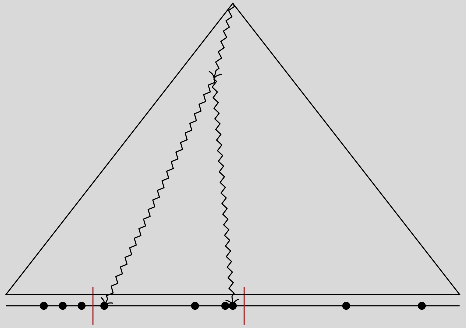
- build BBST where each leaf contains a point
- inner node v store splitting value x_v

1-Dimensional Range Searching (1/2)

Karlsruhe Institute of Technology

- 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

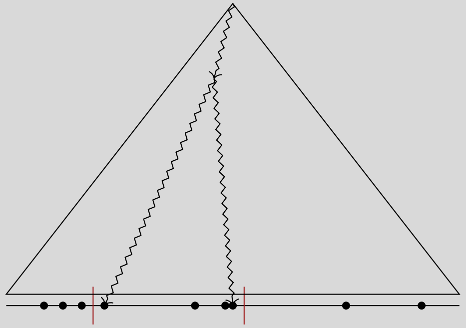


1-Dimensional Range Searching (1/2)

- 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)

- how long does it take to report all children of a subtree with k leaves in a BBST? **PINGO**

1-Dimensional Range Searching (2/2)

Karlsruhe Institute of Technology

- how long does it take to report all children of a subtree with k leaves in a BBST? **PINGO**

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

1-Dimensional Range Searching (2/2)

- how long does it take to report all children of a subtree with k leaves in a BBST? **PINGO**

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)

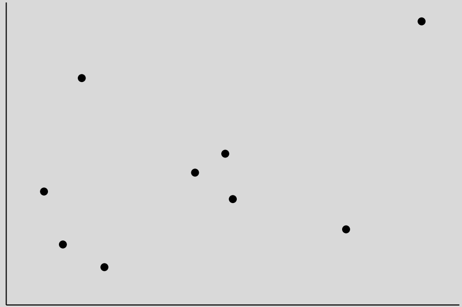
- reporting all children in a subtree requires $O(occ)$ time
- BBST has depth $O(\log n)$
- search paths starting at v have length $O(\log n)$
- report all subtrees to the right of the left path
- report all subtrees to the left of the right path

2-Dimensional Rectangular Range Searching

Important

- assume no two points have the same x- or y-coordinate $\Rightarrow$ general position

- 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

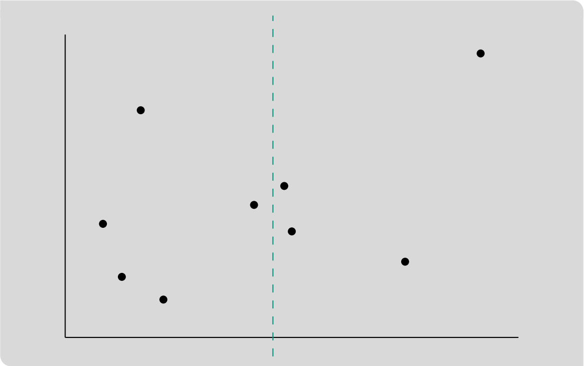


2-Dimensional Rectangular Range Searching

Important

- assume no two points have the same x- or y-coordinate $\Rightarrow$ general position

- 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



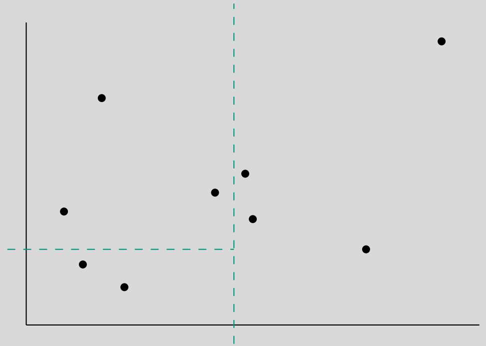
2-Dimensional Rectangular Range Searching

Karlsruhe Institute of Technology

Important

- assume no two points have the same x- or y-coordinate ⇒ general position

- 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



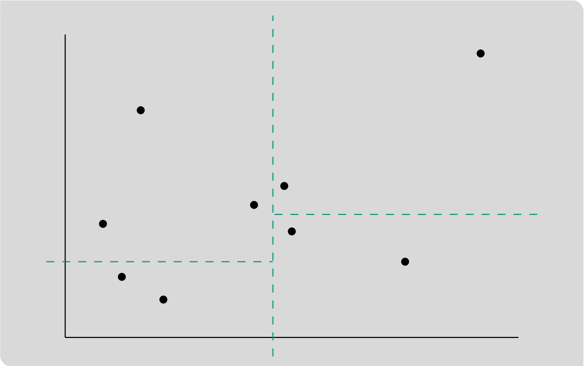
2-Dimensional Rectangular Range Searching

Karlsruhe Institute of Technology

Important

- assume no two points have the same x- or y-coordinate $\Rightarrow$ general position

- 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

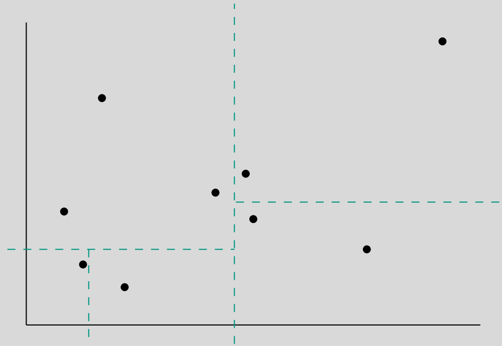


2-Dimensional Rectangular Range Searching

Important

- assume no two points have the same x- or y-coordinate $\Rightarrow$ general position

- 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

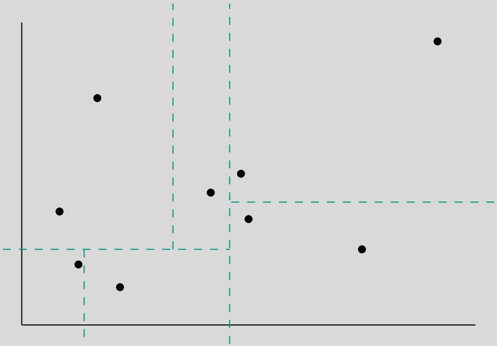


2-Dimensional Rectangular Range Searching

Important

- assume no two points have the same x- or y-coordinate $\Rightarrow$ general position

- 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



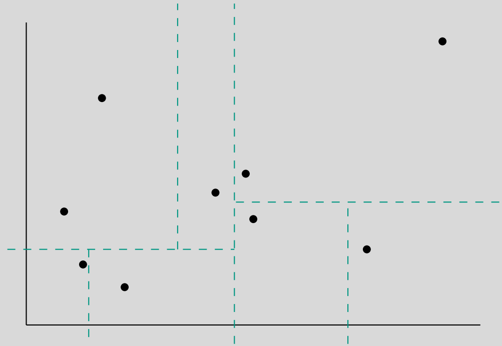
2-Dimensional Rectangular Range Searching

Karlsruhe Institute of Technology

Important

- assume no two points have the same x- or y-coordinate $\Rightarrow$ general position

- 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



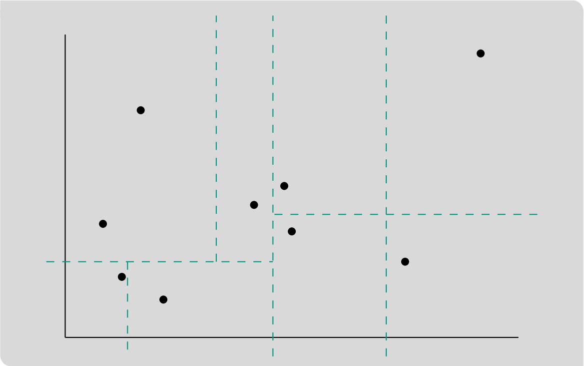
2-Dimensional Rectangular Range Searching

Karlsruhe Institute of Technology

Important

- assume no two points have the same x- or y-coordinate ⇒ general position

- 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



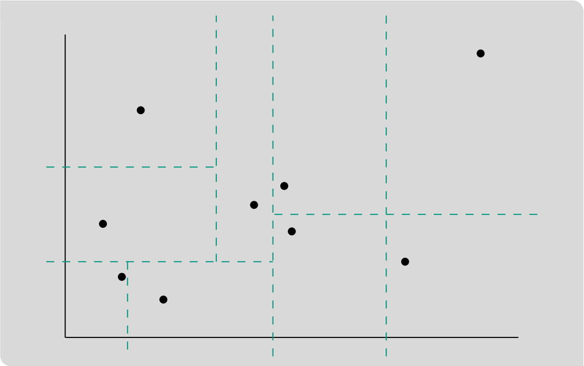
2-Dimensional Rectangular Range Searching

Karlsruhe Institute of Technology

Important

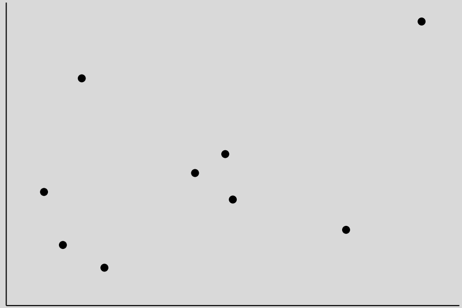
- assume no two points have the same x- or y-coordinate $\Rightarrow$ general position

- 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

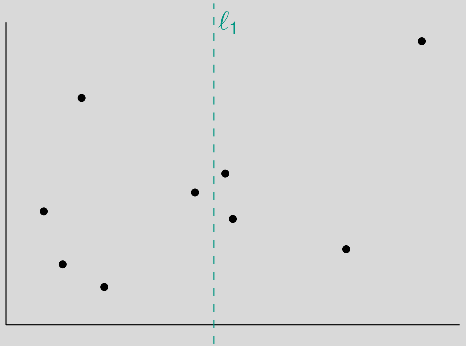


- splitting in linear time is complicated
- better presort based on x- and y-coordinate
- inner nodes store splitter (line)

Kd-Trees (1/4)

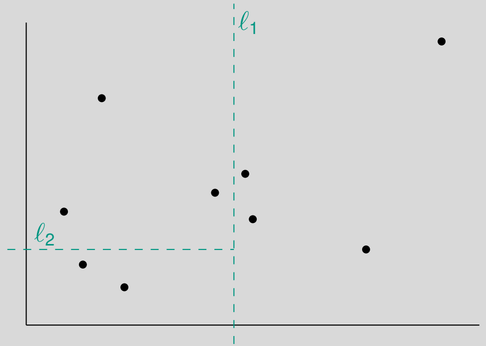
- considering the 2-dimensional case
- each inner node at an even depth
  - splits the leaves in its subtree in half
  - using the x-coordinate
- each inner node at an odd depth
  - splits the leaves in its subtree in half
  - using the y-coordinate
- until each region contains a single point
- each 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 (1/4)

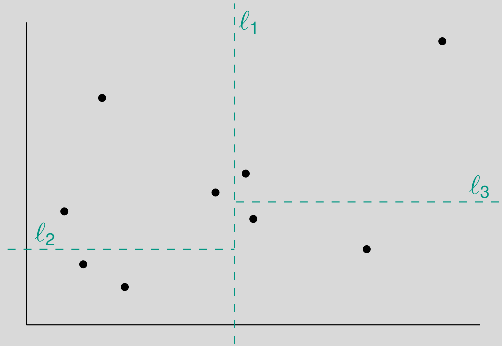
- considering the 2-dimensional case
- each inner node at an even depth
  - splits the leaves in its subtree in half
  - using the x-coordinate
- each inner node at an odd depth
  - splits the leaves in its subtree in half
  - using the y-coordinate
- until each region contains a single point
- each 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 (1/4)

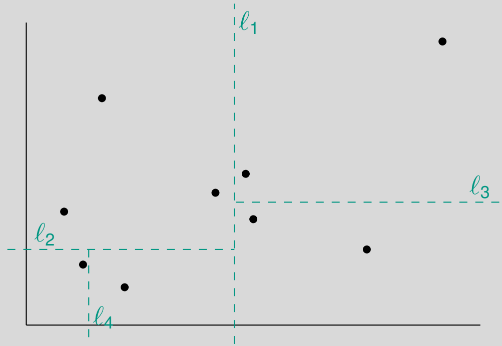
- considering the 2-dimensional case
- each inner node at an even depth
  - splits the leaves in its subtree in half
  - using the x-coordinate
- each inner node at an odd depth
  - splits the leaves in its subtree in half
  - using the y-coordinate
- until each region contains a single point
- each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

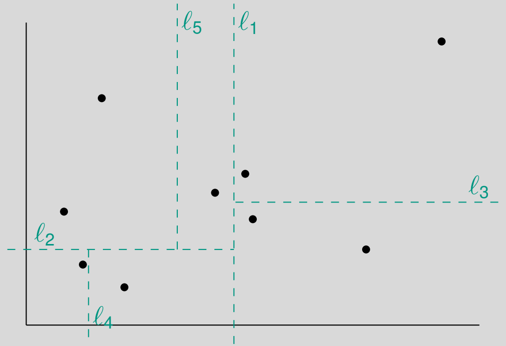


- splitting in linear time is complicated
- better presort based on *x*- and *y*-coordinate
- inner nodes store splitter (line)

Kd-Trees (1/4)

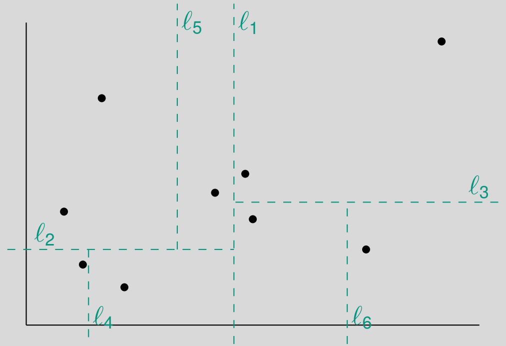
- considering the 2-dimensional case
- each inner node at an even depth
  - splits the leaves in its subtree in half
  - using the *x*-coordinate
- each inner node at an odd depth
  - splits the leaves in its subtree in half
  - using the *y*-coordinate
- until each region contains a single point
- each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

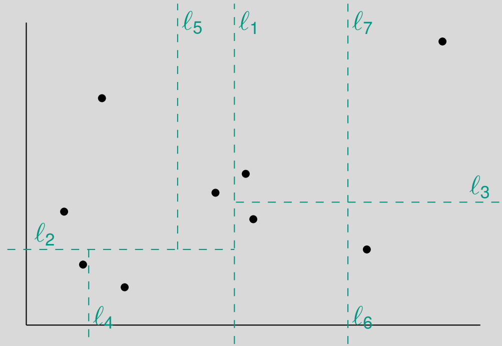


- splitting in linear time is complicated
- better presort based on x- and y-coordinate
- inner nodes store splitter (line)

Kd-Trees (1/4)

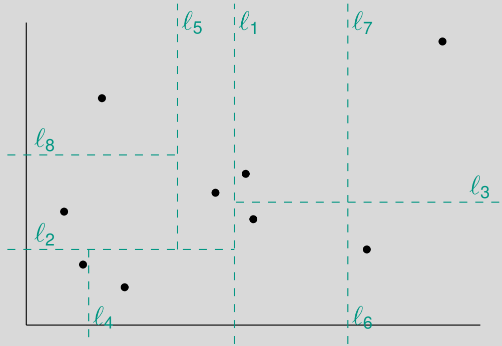
- considering the 2-dimensional case
- each inner node at an even depth
  - splits the leaves in its subtree in half
  - using the x-coordinate
- each inner node at an odd depth
  - splits the leaves in its subtree in half
  - using the y-coordinate
- until each region contains a single point
- each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

Kd-Trees (2/4)

Karlsruhe Institute of Technology

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

Kd-Trees (2/4)

Karlsruhe Institute of Technology

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
- presorting in same time bound

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

Kd-Trees (3/4)

Karlsruhe Institute of Technology

- 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 query not necessary
- current region can be computed during query
- using splitters

Kd-Trees (3/4)

Karlsruhe Institute of Technology

- 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 query not necessary
- current region can be computed during query
- using splitters

- example on the board

Kd-Trees (4/4)

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 $O(\sqrt{n} + occ)$ time

Kd-Trees (4/4)

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 $O(\sqrt{n} + occ)$ time

Proof (Sketch)

- $O(occ)$ 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

Kd-Trees (4/4)

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 $O(\sqrt{n} + occ)$ time

Proof (Sketch)

- $O(occ)$ 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 $\lceil n/4 \rceil$ ℹ 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

Teaser: Other Space-Partitioning Search Trees

- Quadtrees
  - recursive partition of input space into four children (top-down)
  - generalizes to higher dimensions (Octtree)
  - often used in computer graphics

Teaser: Other Space-Partitioning Search Trees

- Quadtrees
  - recursive partition of input space into four children (top-down)
  - generalizes to higher dimensions (Octtree)
  - often used in computer graphics
- R-Trees
  - recursively group nearby objects into minimal bounding boxes (bottom-up)
  - works also for complex shapes, not only points
  - many variants exist (R^*-Trees, R+Trees)
  - often used in spatial databases

Teaser: Other Space-Partitioning Search Trees

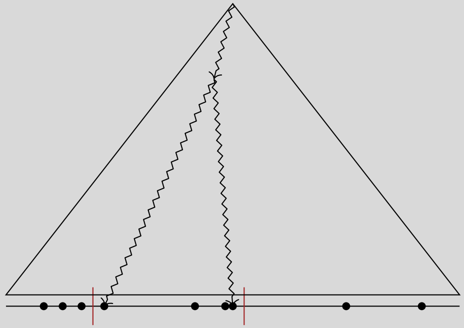
- Quadtrees
  - recursive partition of input space into four children (top-down)
  - generalizes to higher dimensions (Octtree)
  - often used in computer graphics
- R-Trees
  - recursively group nearby objects into minimal bounding boxes (bottom-up)
  - works also for complex shapes, not only points
  - many variants exist (R^*-Trees, R+Trees)
  - often used in spatial databases

Example on the board

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

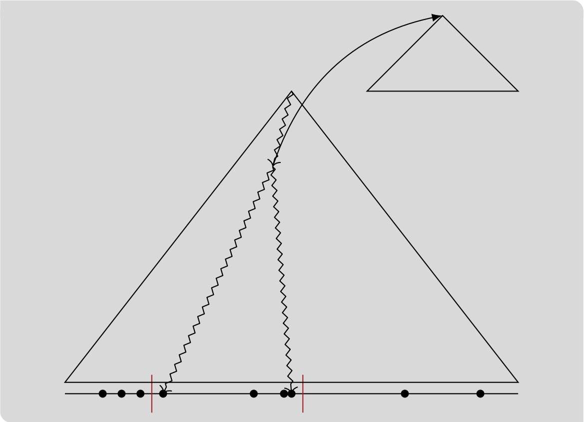
- space-query-time trade-off
- faster queries but larger



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

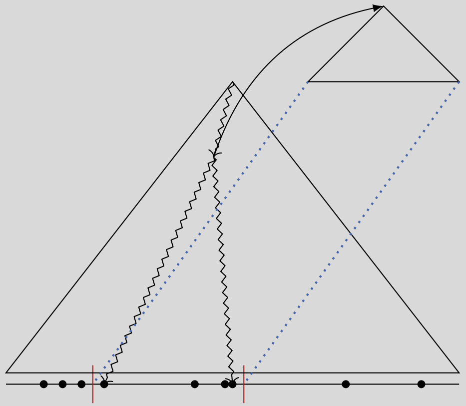
- space-query-time trade-off
- faster queries but larger



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



Range Trees (2/4)

- the BBST for the x-coordinates requires $O(n)$ words of space
- how much space do the associated BBSTs require in total? **PINGO**

Range Trees (2/4)

Karlsruhe Institute of Technology

- the BBST for the x-coordinates requires $O(n)$ words of space
- how much space do the associated BBSTs require in total? **PINGO**

Lemma: Space Range Tree

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

Range Trees (2/4)

- the BBST for the x-coordinates requires $O(n)$ words of space
- how much space do the associated BBSTs require in total? **PINGO**

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

Range Trees (2/4)

- the BBST for the x-coordinates requires $O(n)$ words of space
- how much space do the associated BBSTs require in total? **PINGO**

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

Range Trees (2/4)

- the BBST for the x-coordinates requires $O(n)$ words of space
- how much space do the associated BBSTs require in total? **PINGO**

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 ℹ 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

Range Trees (3/4)

- 2-dimensional rectangular range search reduced to two 1-dimensional range searches
- look in BBST for x-coordinates ℹ 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 $O(\log^2 n + occ)$ time

Range Trees (3/4)

- 2-dimensional rectangular range search reduced to two 1-dimensional range searches
- look in BBST for x-coordinates ℹ 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 $O(\log^2 n + occ)$ time

Proof (Sketch)

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

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

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 $O(\log^d n + occ)$ time

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 $O(\log^d n + occ)$ 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 $Q_d(n) = O(\log^d n)$
- $O(occ)$ time for reporting

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 $O(\log^d n + occ)$ 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 $Q_d(n) = O(\log^d n)$
- $O(occ)$ 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 $S_d(n) = O(n \log^{d-1} n)$

Fractional Cascading (1/2)

- sorted sets $S_1, \ldots, S_m$
- $|S_1| = n$ and $S_{i+1} \subseteq S_i$
- report elements in range $[x..x']$ in $S_1, \ldots, S_m$

Fractional Cascading (1/2)

- 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? **PINGO**

Fractional Cascading (1/2)

- 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? **PINGO**
- $O(m \log n + occ)$ time

Fractional Cascading (1/2)

- 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? **PINGO**
- $O(m \log n + occ)$ time
- $O(m + \log n + occ)$ time possible with fractional cascading

Fractional Cascading (1/2)

- 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? **PINGO**
- $O(m \log n + occ)$ time
- $O(m + \log n + occ)$ 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 $S_{i+1} \subseteq S_i$

Fractional Cascading (2/2)

Karlsruhe Institute of Technology

Lemma: Fractional Cascading

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 $O(m + \log n + occ)$ time

Fractional Cascading (2/2)

Karlsruhe Institute of Technology

Lemma: Fractional Cascading

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 $O(m + \log n + occ)$ 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 $O(occ)$ time
- following pointer to S_3 requires $O(1)$ time
- repeat m times
- total: $O(m + \log n + occ)$ time

Fractional Cascading (2/2)

Lemma: Fractional Cascading

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 $O(m + \log n + occ)$ 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 $O(occ)$ time
- following pointer to S_3 requires $O(1)$ time
- repeat m times
- total: $O(m + \log n + occ)$ 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

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

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 $O(\log n + occ)$ time

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

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 $O(\log n + occ)$ time

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 $O(1 + occ_a)$ time
- each point is reported once
- total time: $O(\log n + occ)$

General Sets of Points (1/2)

- all solutions requires unique x and y-coordinates
- big limitation for applications
- remember database motivation

General Sets of Points (1/2)

Karlsruhe Institute of Technology

- all solutions requires unique x and y-coordinates
- 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 $(x|k) < (x'|k') \iff x < x'$ or $(x = x'$ and $k < K'))$

General Sets of Points (1/2)

- all solutions requires unique x and y-coordinates
- 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 $(x|k) < (x'|k') \iff x < x'$ or $(x = x'$ and $k < K'))$

- range queries $[x..x'] \times [y..y']$ become

$$[(x| -\infty)..(x'|\infty)] \times (y| -\infty)..[(y'|\infty)]$$

General Sets of Points (2/2)

- all solutions requires unique x and y-coordinates
- big limitation for applications
- remember database motivation
- if exact positions are not important to application

General Sets of Points (2/2)

- all solutions requires unique x and y-coordinates
- big limitation for applications
- remember database motivation
- if exact positions are not important to application

- random perturbation: $x + \delta \sim U(-\epsilon, \epsilon)$
- same for y-coordinates

General Sets of Points (2/2)

- all solutions requires unique x and y-coordinates
- big limitation for applications
- remember database motivation
- if exact positions are not important to application

- random perturbation: $x + \delta \sim U(-\epsilon, \epsilon)$
- same for y-coordinates

- range queries $[x..x'] \times [y..y']$ become

$$[(x - \epsilon)..(x' + \epsilon)] \times (y - \epsilon)..[(y' + \epsilon)]$$

Conclusion and Outlook

This Lecture

- orthogonal range searching

Advanced Data Structures