

# DSC 190

DATA STRUCTURES & ALGORITHMS

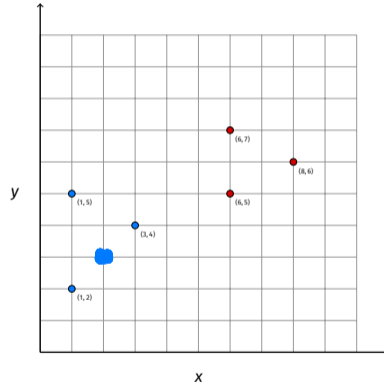
Lecture 6 | Part 1

**Today's Lecture**

# Nearest Neighbors

- ▶ Finding the closest data point to a query point is a common operation.
- ▶ In machine learning, at the core of the **nearest neighbor classifier**.

# NN Classifier



# NN Query

- ▶ **Given:** a data set  $X$  of  $n$  points in  $\mathbb{R}^d$  and a **query** point,  $p \in \mathbb{R}^d$ .
- ▶ **Return:** the point in  $X$  that is nearest<sup>1</sup> to  $p$

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<sup>1</sup>In terms of Euclidean distance, though other distances can be considered.

# Approach #1: Brute Force

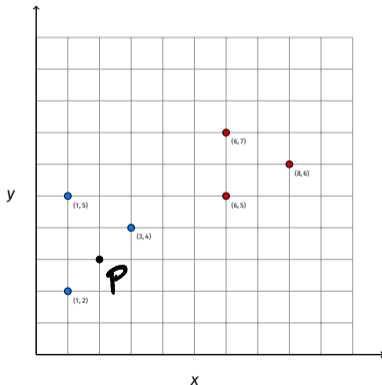
- ▶ Compute distance between  $p$  and every point  $x \in X$ , keep closest.
- ▶ Time:  $\Theta(nd)$

$\Theta(d)$  = time needed  
to compute  
distance

```
def brute_force_nn_search(data, p):  
    """Find nearest neighbor.  
  
    Parameters  
    -----  
    data : np.ndarray  
        An n x d array of points.  
    p : np.ndarray  
        A d-array representing the query point.  
  
    Returns  
    -----  
    nn : np.ndarray  
        The closest point.  
    nn_distance : float  
        Distance to closest point.  
  
    """  
    distances = np.sqrt(np.sum((data - p)**2, axis=1))  
    ix_of_nn = np.argmin(distances)  
    nn = data[ix_of_nn]  
    nn_distance = distances[ix_of_nn]  
    return (nn, nn_distance)
```

# Intuitively...

- ▶ ...we can do better. We only need to look at region close to  $p$ .

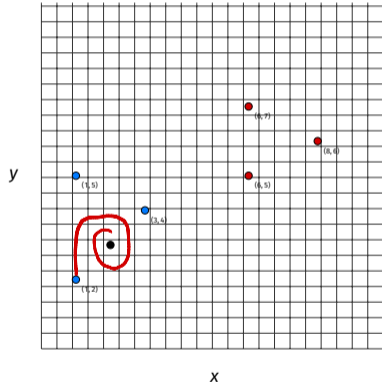


## Approach #2

- ▶ Build a grid.
- ▶ To query NN, find cell containing  $p$ .
- ▶ Start search in  $p$ 's cell, move outwards.



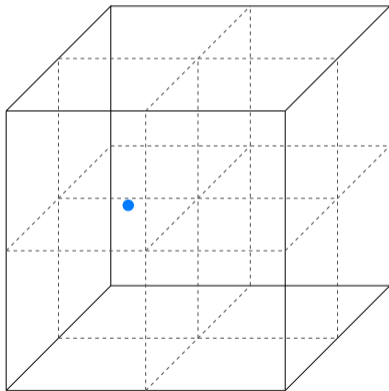
# Intuitively...



# Problems



- ▶ How do we choose grid cell size?
  - ▶ Too big: cells contain a lot of points = brute force.
  - ▶ Too small: Most of the cells are empty.
  - ▶ “Just right” for one region might be too big/small for another region.
  
- ▶ Number of cells grows **exponentially** with dimension.



# Today

- ▶ We'll refine the idea of a grid.
- ▶ Adapt cell placement/size to the data.
- ▶ Result: **k-d trees**.

# k-d Trees

- ▶ Will speed up NN queries in low dimensions ( $<10$ ) from  $\Theta(n)$  to  $\Theta(\log n)$ .
- ▶ But will be just as bad as brute force in high dimensions.

# DSC 190

DATA STRUCTURES & ALGORITHMS

Lecture 6 | Part 2

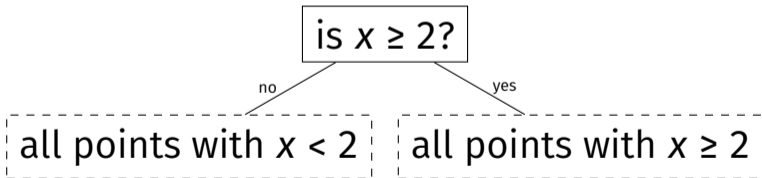
**k-d Trees**

# k-d Trees

- ▶ **Binary search tree** for multidimensional data.
- ▶ Now: structure & properties.
- ▶ Next section: how to query them.
- ▶ Next next section: how to construct them.

# Internal Nodes

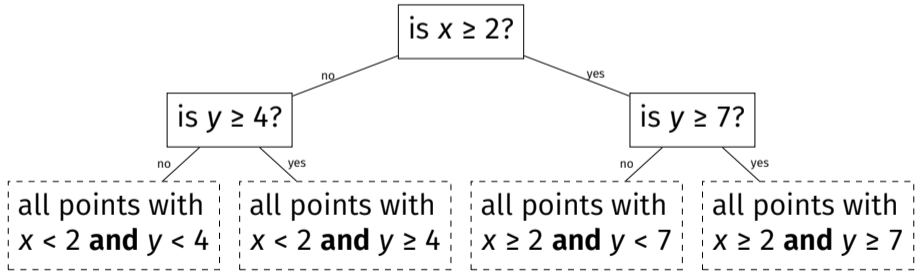
- ▶ Internal nodes are **threshold questions**.
  - ▶ can be of form  $x \geq \tau?$  or  $y \geq \tau?$  in 2-d.
  - ▶ can be of form  $x \geq \tau?$  or  $y \geq \tau?$  or  $z \geq \tau?$  in 3-d.
  - ▶ etc.





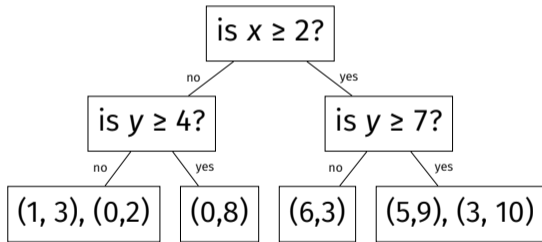
# Internal Nodes

- ▶ A path forms a **conjunction**.



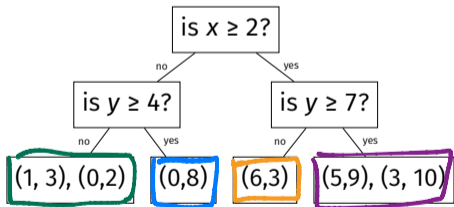
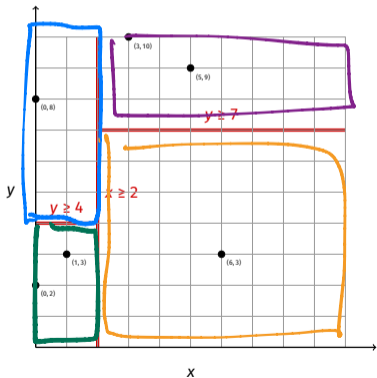
# Leaf Nodes

- ▶ Leaf nodes are (collections of) points.



# Partitioning

- ▶ Each internal node **splits** space.



# k-d Trees in Python

```
from dataclasses import dataclass
from typing import Union, Optional
import numpy as np

@dataclass
class KDInternalNode:
    # the left and right children can be internal nodes
    # or numpy arrays of points (leaf nodes)
    left: Union['KDInternalNode', np.ndarray]
    right: Union['KDInternalNode', np.ndarray]

    # the threshold tau in the question
    threshold: float

    # the dimension used in the question
    dimension: int
```

# DSC 190

DATA STRUCTURES & ALGORITHMS

Lecture 6 | Part 3

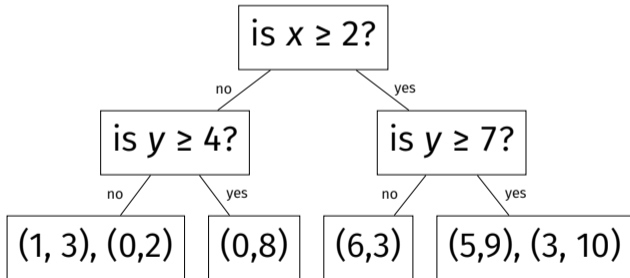
**Queries on k-d Trees**

# Types of Queries

- ▶ Standard query:
  - ▶ Is  $(1, 5)$  in the tree?
- ▶ Nearest neighbor query:
  - ▶ Return the nearest neighbor(s) of  $(1, 5)$ .

# Standard Queries

- ▶ Is (6,3) in the tree? Is (1, 5) in the tree?



# Standard Queries

- ▶ Similar to BST query.
  - ▶ Recursively choose left/right by answering question.
  - ▶ Brute-force linear search on leaf (if needed).
- ▶ Takes  $O(h)$  time, where  $h$  is height of the tree<sup>2</sup>.

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<sup>2</sup>Assuming each leaf has a bounded number of points.

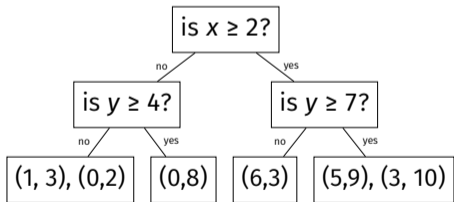
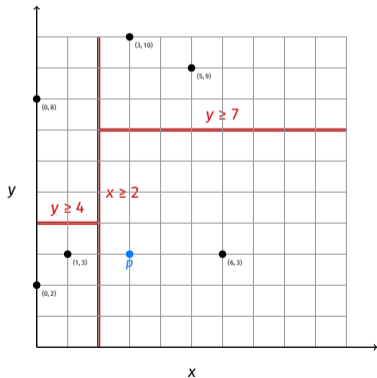


# Nearest Neighbor Queries

- ▶ Given query point  $p = (x, y)$ , find nearest neighbor in tree.
- ▶ Can we just do a standard query?
  - ▶ Find cell that *would* contain  $(x, y)$ .
  - ▶ Return closest neighbor within that cell.

# No

► Example:  $p = (3, 3)$ .



## Main Idea

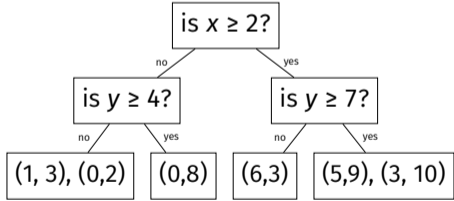
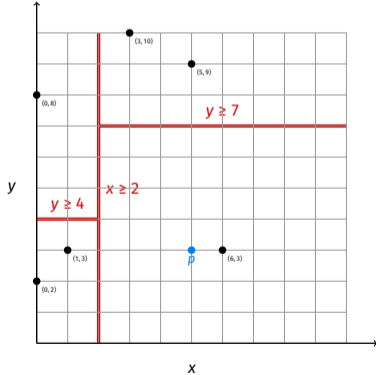
It is not always sufficient to only check the cell that  $p$  would be placed in. You may also need to check neighboring cells (which can be very far away in the tree).

## Brute Force?

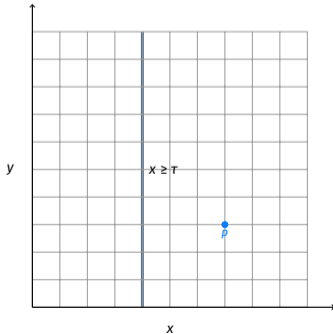
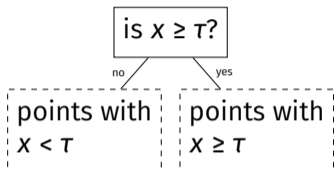
- ▶ This suggests we need to traverse the whole tree.
- ▶ But we can actually do much better.
- ▶ Intuitively, some branches can be ruled out (**pruned**).

# Example

- ▶ Example:  $p = (5, 3)$ .

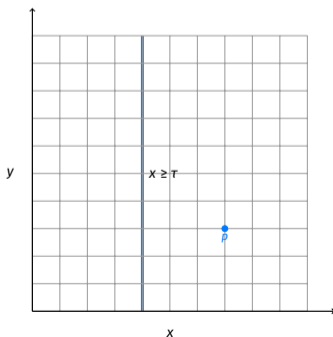
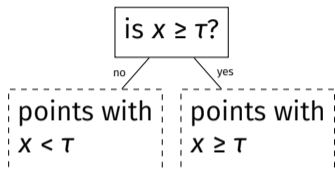


# Bounding Branches



- ▶ **Observation:** let  $d_{\text{bound}}$  be distance from  $p$  to the boundary.
- ▶ Then the closest a point in the other branch can be to  $p$  is  $d_{\text{bound}}$
- ▶ If we search and find a point whose distance to  $p$  is less than  $d_{\text{bound}}$ , **we do not need to search other branch.**

# Bounding Branches



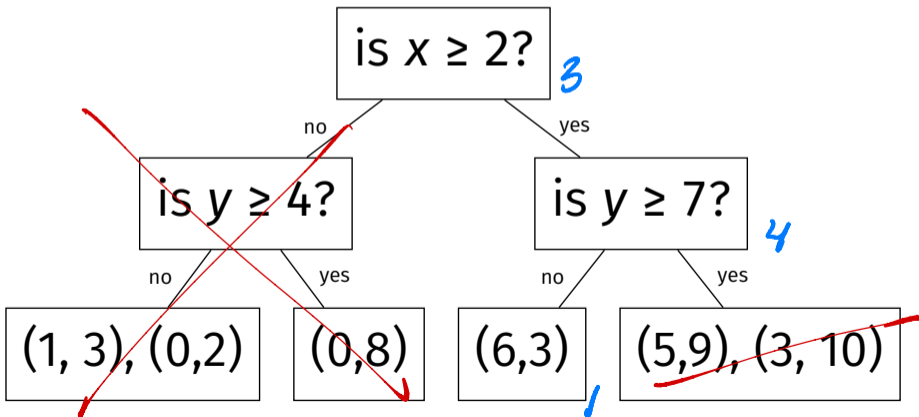
To query NN of  $(x, y)$ :

- ▶ Search right branch first if  $x \geq t$ , otherwise search left branch first.
- ▶ Let  $d_{nn}$  be the distance from  $p$  to the closest point found.
- ▶ Let  $d_{bound}$  be the distance from  $p$  to boundary.
- ▶ Search other branch only if  $d_{bound} < d_{nn}$ .

Apply this idea recursively.

# Example

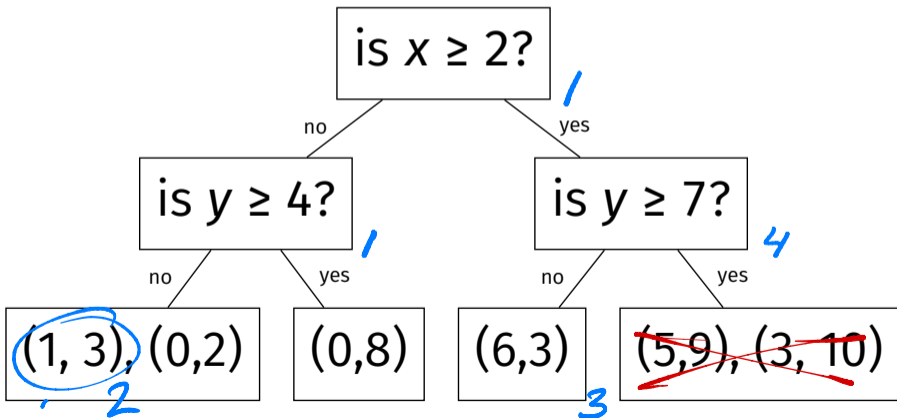
- ▶ NN Query: (5, 3)





# Example

- ▶ NN Query: (3, 3)



```
def nn_query(node, p):
    if isinstance(node, np.ndarray):
        return brute_force_nn_search(node, p)
    else:
        # find the most likely branch
        if p[node.dimension] >= node.threshold:
            most_likely_branch, other_branch = node.right, node.left
        else:
            most_likely_branch, other_branch = node.left, node.right

        # compute distance to boundary
        distance_to_boundary = abs(p[node.dimension] - node.threshold)

        # find nn within most likely branch
        nn, nn_distance = nn_query(most_likely_branch, p)

        # check the other branch, but only if necessary
        if distance_to_boundary < nn_distance:
            nn_other, nn_other_distance = nn_query(other_branch, p)

            # check if the nn within this branch is closer
            if nn_other_distance < nn_distance:
                nn = nn_other
                nn_distance = nn_other_distance

    return nn, nn_distance
```

# k-NN Search

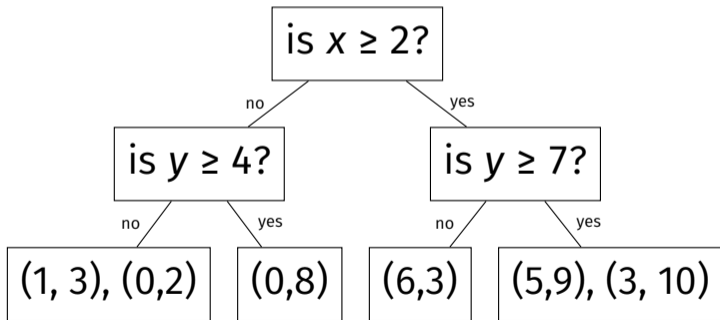
- ▶ Sometimes we want to find  $k$  nearest neighbors.
- ▶ Keep a max heap of best  $k$  so far.
- ▶ Check branch if distance to boundary  $<$   $k$ th closest.

# Analysis

- ▶ Assume each leaf has bounded number of points.
- ▶ Best case:  $\Theta(h) \rightarrow \Theta(\log n)$  if balanced
- ▶ Worst case:  $\Theta(n)$ .
  - ▶ We may be unable to rule out many of the branches.
  - ▶ Can occur even if tree is balanced.
  - ▶ Especially if query point far from data.
- ▶ Note: balancing is difficult, but possible.

# Example of Worst Case

- ▶ NN Query: (20, 20)
- ▶ Closest point is (5, 9) at distance  $\approx 19$



# Performance Degradation

- ▶ In small dimensions, NN lookup usually takes  $\Theta(\log n)$ .
- ▶ We'll see performance **degrades** to  $\Theta(n)$  (brute force) as dimensionality  $\rightarrow \infty$ .
- ▶ **Curse of Dimensionality**

# DSC 190

DATA STRUCTURES & ALGORITHMS

Lecture 6 | Part 4

**Constructing k-d Trees**

# Construction

- ▶ **Given:** a set of  $n$  data points in  $\mathbb{R}^d$
- ▶ **Construct:** a k-d tree containing these points.



# Caveats

- ▶ There are many variations on k-d tree construction.
- ▶ We'll describe one popular approach.
- ▶ **Assumption: offline** construction.
  - ▶ Have all of the data at once (no insert/delete).

# Idea

- ▶ Starting with  $n$  points, either:
  - ▶ make internal node by splitting ( $x \geq \tau$ ?)
  - ▶ make leaf node containing the points
  
- ▶ Apply this strategy recursively.
  
- ▶ Questions:
  - ▶ Do we split, or do we make a leaf?
  - ▶ If we split:
    - ▶ What dimension to split on?
    - ▶ What threshold to use?

## Q1: Do we split?

- ▶ Take parameter  $M$  (max leaf size).
- ▶ If  $n < M$ , don't split.
- ▶ **Reason:** For small  $n$ , brute force is actually faster (less overhead).

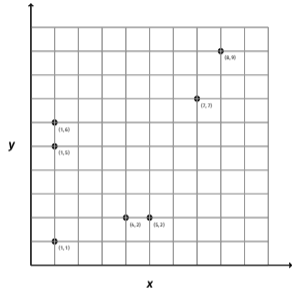
## Q2: Which dimension to split on?

- ▶ Choose dimension with largest **spread**.
  - ▶ Difference between largest and smallest values.
  - ▶ Calculated using only points in **this** subtree.
- ▶ **Alternatively:** round-robin. Split  $x, y, z, x, y, \dots$

## Q3: What threshold to use?

- ▶ Need threshold,  $\tau$ .
- ▶ Use median value in splitting dimension.
  - ▶ Calculated using only points in **this** subtree.
  - ▶ Guaranteed to produce balanced tree.
- ▶ **Alternatively:** randomly-selected pivot, or median of random selection

Set  $M = 2$ , use median and spread for splitting. We start with data:



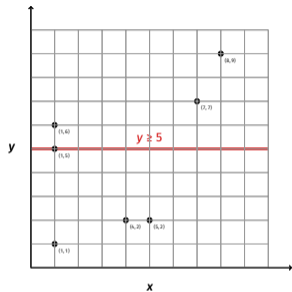
$(1,1), (4,2), (5,2), (1,5), (1,6), (7,7), (8,9)$

x	y
4	2
1	1
5	2
1	6
7	7
8	9
2	5

- ▶ Spread of x: 7
- ▶ Spread of y: 8
- ▶ Use y as splitting dimension.
- ▶ Median of y: 5.

$$y = 5$$

Set  $M = 2$ , use median and spread for splitting. We start with data:

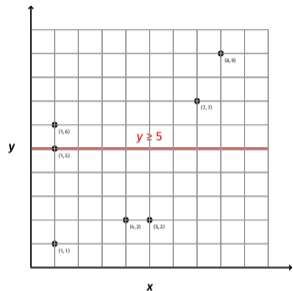


x	y
4	2
1	1
5	2
1	6
7	7
8	9
2	5

is  $y \geq 5$ ?

$(1,1), (4,2), (5,2)$      $(1,5), (1,6), (7,7), (8,9)$

- ▶ Spread of  $x$ : 7
- ▶ Spread of  $y$ : 8
- ▶ Use  $y$  as splitting dimension.
- ▶ Median of  $y$ : 5.



is  $y \geq 5$ ?

(1,1), (4,2), (5,2)

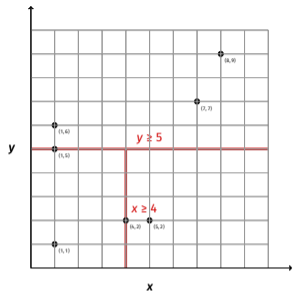
(1,5), (1,6), (7,7), (8,9)

Recurse on left child. Data becomes:

x	y
4	2
1	1
5	2

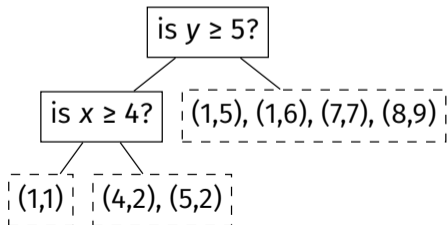
- ▶ Spread of x: 4
- ▶ Spread of y: 1
- ▶ Use x as splitting dimension.
- ▶ Median of x: 4.



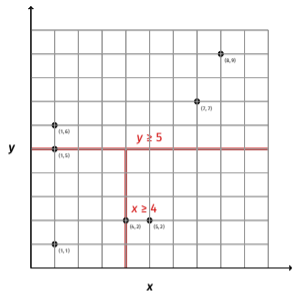


Recurse on left child. Data becomes:

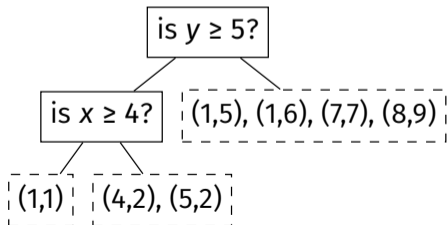
x	y
4	2
1	1
5	2

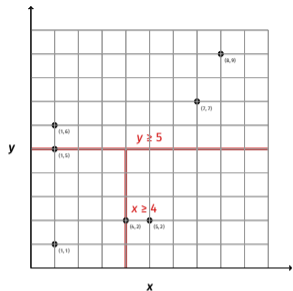


- ▶ Spread of x: 4
- ▶ Spread of y: 1
- ▶ Use x as splitting dimension.
- ▶ Median of x: 4.

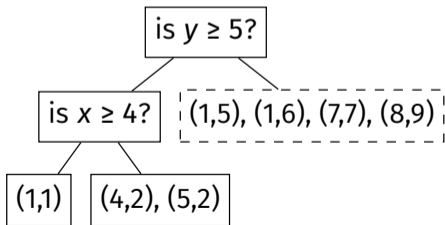


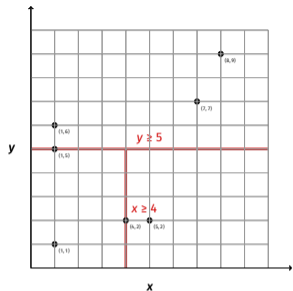
Recurse on children. Since size  $\leq M$ , these become leaf nodes.





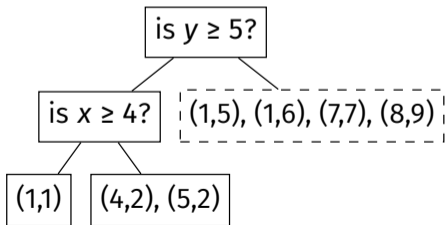
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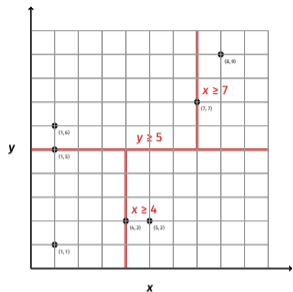


Unroll recursion, now recurse down right side of tree. Data becomes:

x	y
1	6
7	7
8	9
2	5

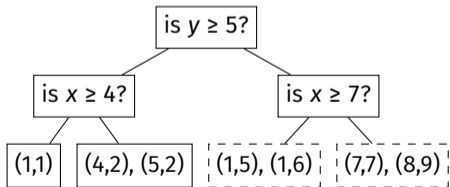


- ▶ Spread of x: 7
- ▶ Spread of y: 4
- ▶ Use x as splitting dimension.
- ▶ Median of x: 7 (or 2).

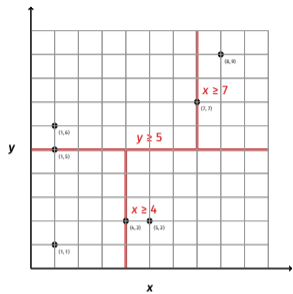


Unroll recursion, now recurse down right side of tree. Data becomes:

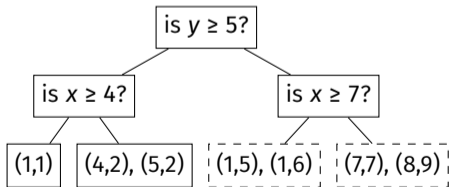
x	y
1	6
7	7
8	9
2	5

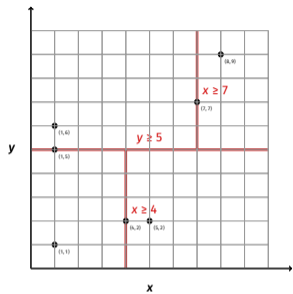


- ▶ Spread of x: 7
- ▶ Spread of y: 4
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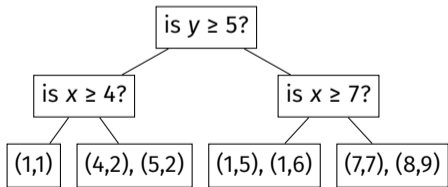


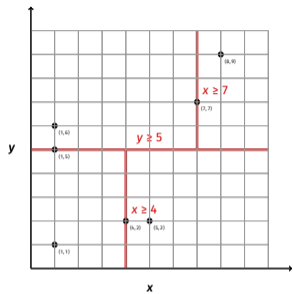
Make leaf nodes, since size  $\leq M$ .



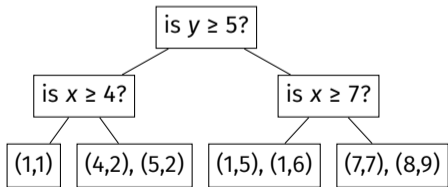


Make leaf nodes, since size  $\leq M$ .





Tree complete!





```
def build_kd_tree(data, m=2):
    if len(data) <= m:
        return data

    # find the dimension with greatest spread
    spread = data.max(axis=0) - data.min(axis=0)
    splitting_dimension = np.argmax(spread)

    # find the median along this dimension
    median = np.median(data[:, splitting_dimension])

    # separate the data into new left and right sets
    # note that this isn't the most efficient since it will
    # produce a copy... better to do an in-place partition
    left_data = data[data[:, splitting_dimension] < median]
    right_data = data[data[:, splitting_dimension] >= median]

    left = build_kd_tree(left_data)
    right = build_kd_tree(right_data)

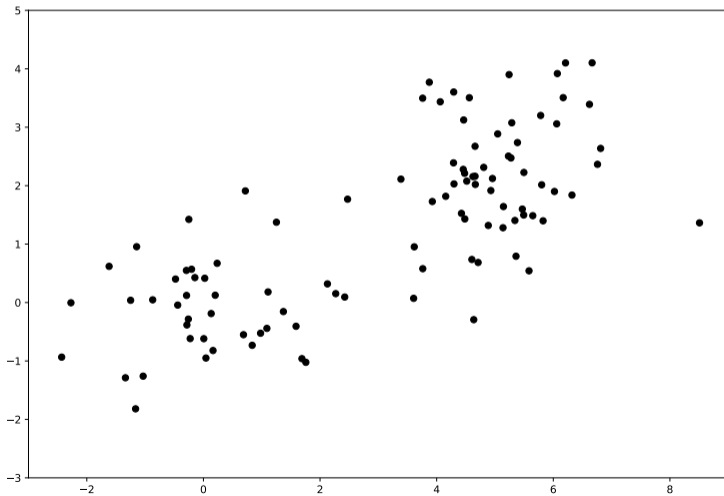
    return KDInternalNode(
        left=left, right=right, threshold=median,
        dimension=splitting_dimension
    )
```

# Analysis

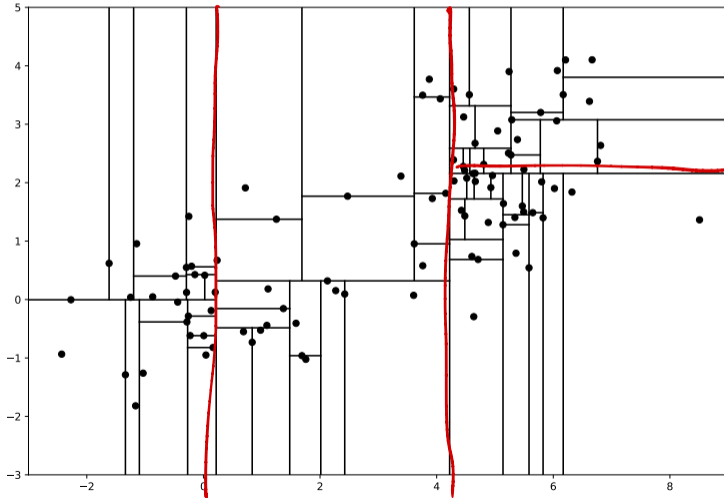
- ▶  $\Theta(k)$  to find median, perform copies, where  $k$  is number of points in subtree.
- ▶ Tree has  $\Theta(\log n)$  levels (since it is balanced).
- ▶ Total time:

$$\underbrace{n}_{\text{level 1}} + \underbrace{(n/2 + n/2)}_{\text{level 2}} + \underbrace{(n/4 + n/4 + n/4 + n/4)}_{\text{level 3}} + \dots = \Theta(n \log n)$$

# Example



# Example



# Demo

- ▶ A demo implementation of k-d trees is available at [dsc190.com](http://dsc190.com)

# DSC 190

DATA STRUCTURES & ALGORITHMS

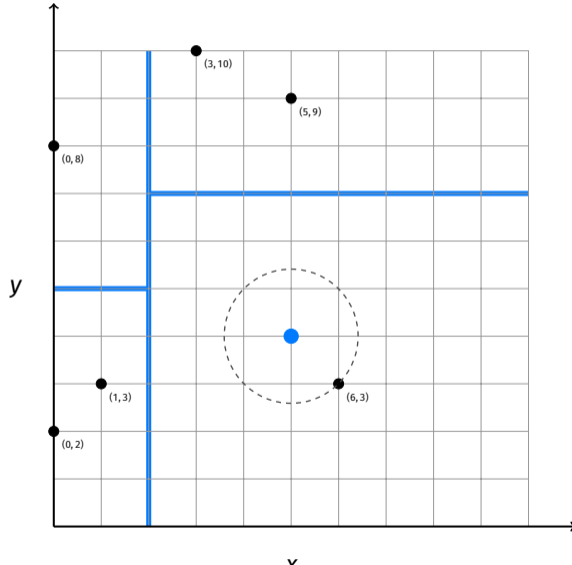
Lecture 6 | Part 5

**Curse of Dimensionality**

# Performance Degradation

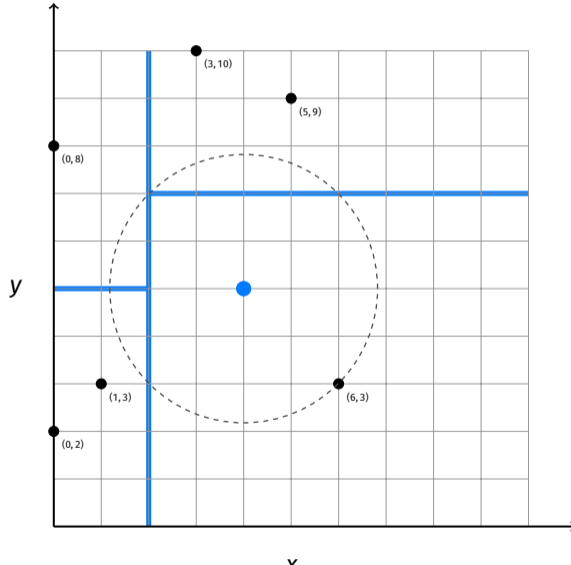
- ▶ Brute force NN search takes  $\Theta(n)$  time.
- ▶ If dimensionality is small, k-d trees take  $\Theta(\log n)$ .
  - ▶ Great speedup!
- ▶ As dimensionality grows, performance **degrades**.
  - ▶ At worst, it is  $\Theta(n)$ .
  - ▶ Becomes just as bad as brute force!
- ▶ Why?

# Explanation #1

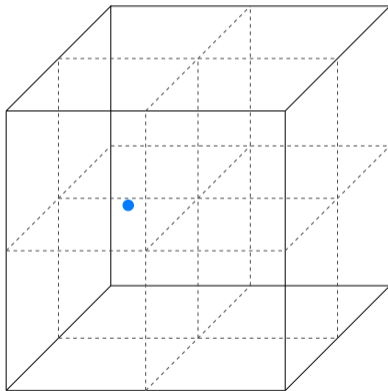




# Explanation #1



# Explanation # 1

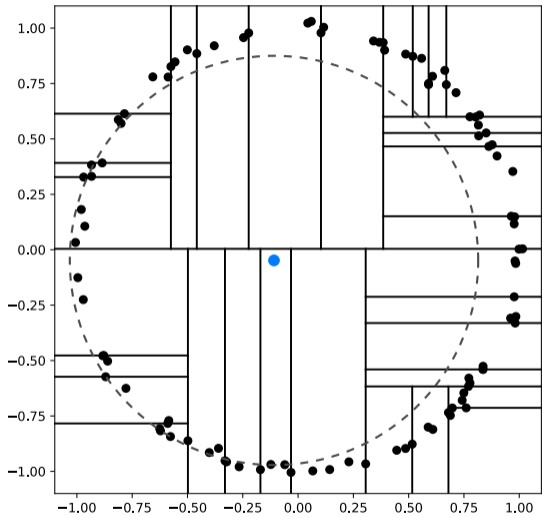


## Main Idea

As  $d$  grows, the number of neighboring cells that we may need to check grows like  $2^d$ .

## Explanation #2

- ▶ We saw that if query point is far away, we cannot rule out branches.
- ▶ The reason? Distance from query to NN is not significantly different from distance between query and other points.



## Surprising Fact

- ▶ In high dimensions<sup>3</sup>, the ratio of the distance to nearest neighbor and distance to furthest neighbor  $\rightarrow 1$ .

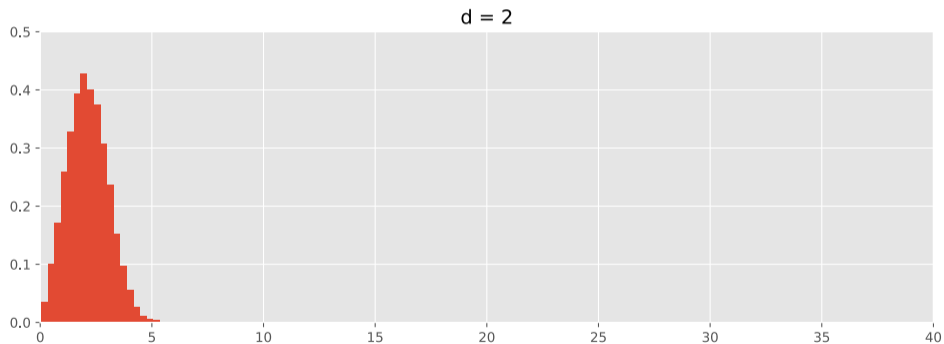
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<sup>3</sup>Under some assumptions on distribution of data.

# Experiment

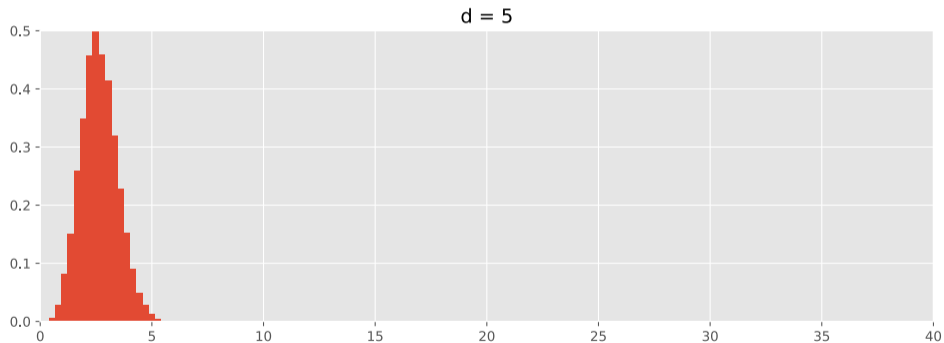
- ▶ Generate random  $d$ -dimensional query vector from multivariate Gaussian.
- ▶ Generate 1000  $d$ -dimensional data points from same Gaussian.
- ▶ Plot distribution of distances.

# Experiment

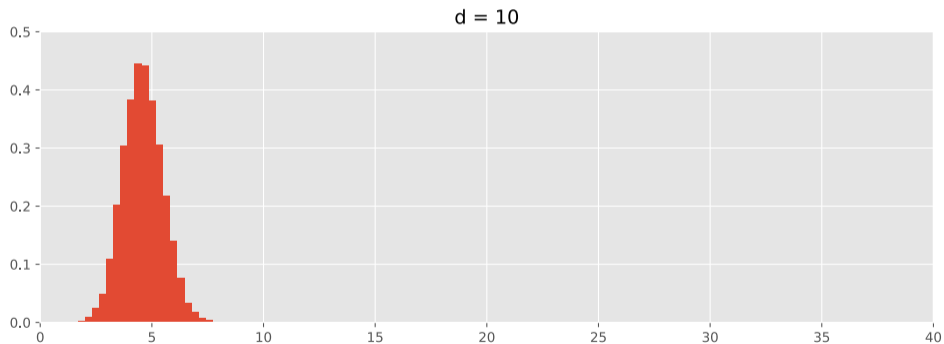




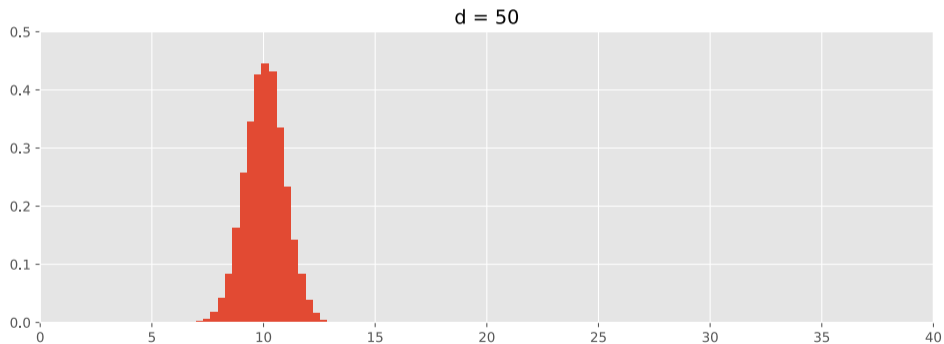
# Experiment



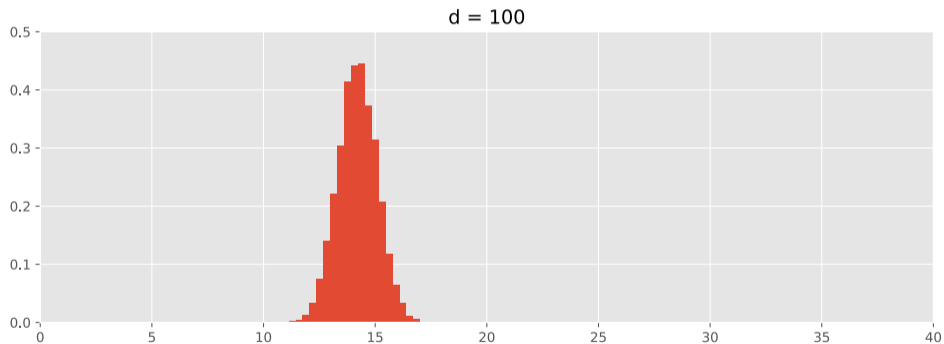
# Experiment



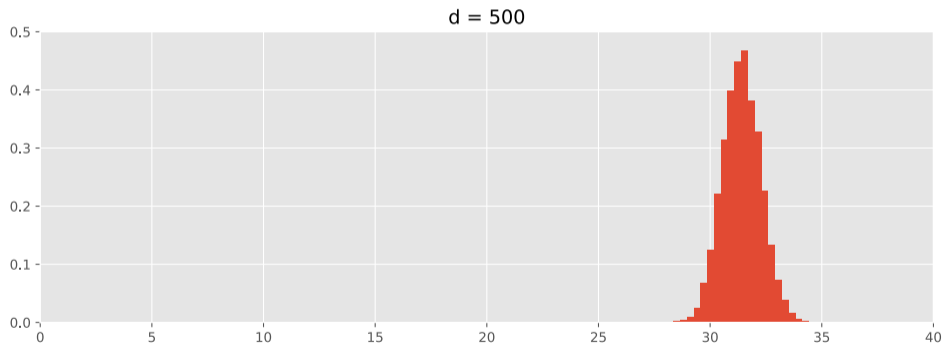
# Experiment



# Experiment



# Experiment



# Experiment

- ▶ Notice: width doesn't change, but center increases.
- ▶ So  $\text{min} = \text{max} - \delta$ , with  $\delta$  constant.

$$\frac{\text{min}}{\text{max}} = 1 - \frac{\delta}{\text{max}}$$

## Explanation #2

- ▶ Every point in data set is approximately equidistant to query point.
- ▶ Can't rule out branches.
- ▶ Have to perform a brute force search.

## Main Idea

In high dimensions, every data point is approximately equidistant to the query point, meaning we can't rule out most branches.



## Main Idea

Not only are k-d trees **inefficient** in high dimensions, Euclidean distance is **less meaningful** in high dimensions, and therefore so is the concept of NN search itself.

# DSC 190

DATA STRUCTURES & ALGORITHMS

Lecture 6 | Part 6

**Approximate Nearest Neighbors**

# Why, exactly?

- ▶ Why do we need the **exact** NN?
- ▶ Often something close would do.
- ▶ Especially if not confident in distance measure.
  - ▶ As is the case in high dimensions.
- ▶ Maybe this can be done faster?

# ANN

- ▶ **Given:** A set of points and a query point,  $p$ .
- ▶ **Return:** An **approximate nearest neighbor**.

## k-D ANNs

- ▶ So far, our k-d trees find **exact** nearest neighbor.
- ▶ But there's a **very** simple way to do ANN query.
- ▶ Idea: prune more aggressively.

# Before

- ▶ Let  $d_{nn}$  be distance from query point to best so far.
- ▶ Let  $d_{bound}$  be distance from query point to boundary.
- ▶ Search branch only if  $d_{bound} < d_{nn}$ .

# Now

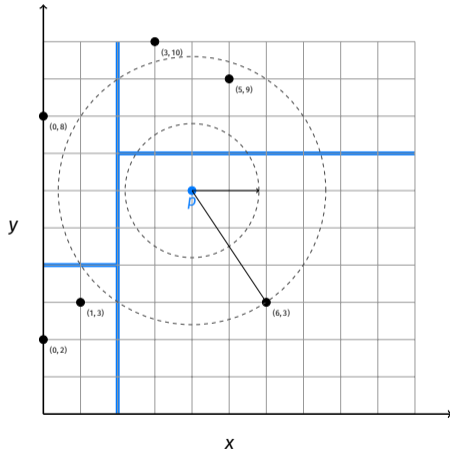
- ▶ Take  $\alpha \geq 1$  as a parameter.
- ▶ Search branch only if  $d_{\text{bound}} < d_{\text{nn}}/\alpha$ .
- ▶ **Idea:** make it easier to toss out branch.
- ▶ If  $\alpha = 1$ ; exact search.
- ▶ If  $\alpha > 1$ ; approximate, faster as  $\alpha$  grows.

# Theory

► Let  $q$  be exact NN, let  $q_{\text{ann}}$  be that found by this strategy.

► Then:

$$d(p, q_{\text{ann}}) \leq \alpha \cdot d(p, q)$$





# Next Time

- ▶ ANNs via **Locality Sensitive Hashing**.