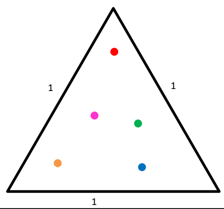
CS4102 Algorithms
Spring 2019

Warm up

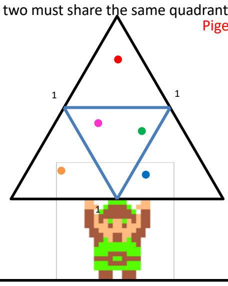
Given 5 points on the unit equilateral triangle, show there's always a pair of distance $\leq \frac{1}{2}$ apart



If points p_1, p_2 in same quadrant, then $\delta(p_1, p_2) \leq \frac{1}{2}$

Given 5 points, two must share the same quadrant

Pigeonhole Principle!



Historical Aside: Master Theorem

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Today's Keywords

- Substitution Method
- Divide and Conquer
- Closest Pair of Points

CLRS Readings

- Chapter 4

Homeworks

- Hw2 released today after class, due Wed 2/13 at 11pm
  - Programming assignment (Python or Java)
  - Divide and conquer

Master Theorem

$$T(n) = aT\left(\frac{n}{b}\right) + f(n)$$

- Case 1: if $f(n) = O(n^{\log_b a - \varepsilon})$ for some constant $\varepsilon > 0$,
  then $T(n) = \Theta(n^{\log_b a})$
- Case 2: if $f(n) = \Theta(n^{\log_b a})$, then $T(n) = \Theta(n^{\log_b a} \log n)$
- Case 3: if $f(n) = \Omega(n^{\log_b a + \varepsilon})$ for some constant $\varepsilon > 0$,
  and if $af\left(\frac{n}{b}\right) \leq cf(n)$ for some constant $c < 1$
  and all sufficiently large n,
  then $T(n) = \Theta(f(n))$

7

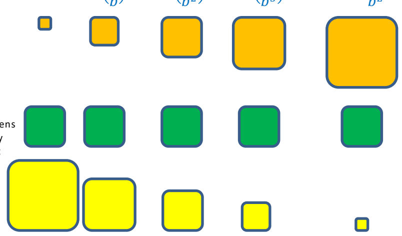
3 Cases

$$T(n) = f(n) + af\left(\frac{n}{b}\right) + a^2 f\left(\frac{n}{b^2}\right) + a^3 f\left(\frac{n}{b^3}\right) + \cdots + a^L f\left(\frac{n}{b^L}\right)$$

Case 1:
Most work happens at the leaves

Case 2:
Work happens consistently throughout

Case 3:
Most work happens at top of tree



8

Recurrence Solving Techniques

- Tree
- Guess/Check
- "Cookbook"
- Substitution

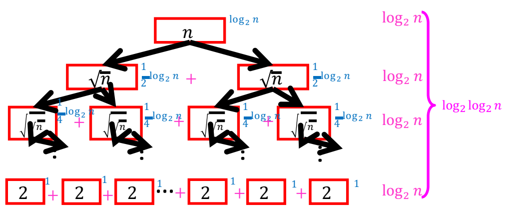
9

Substitution Method

- Idea: take a "difficult" recurrence, re-express it such that one of our other methods applies.
- Example: $T(n) = 2T(\sqrt{n}) + \log_2 n$

Tree method

$T(n) = 2T(\sqrt{n}) + \log_2 n$



$T(n) = O(\log_2 n \cdot \log_2 \log_2 n)$

Substitution Method

- Idea: take a "difficult" recurrence, re-express it such that one of our other methods applies.
- Example: $T(n) = 2T(\sqrt{n}) + \log_2 n$

Let $n = 2^m$, i.e. $m = \log_2 n$

$T(2^m) = 2T\left(2^{\frac{m}{2}}\right) + m$ Rewrite in terms of exponent!

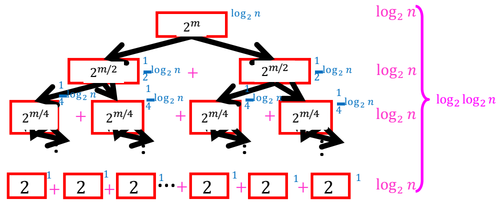
Let $S(m) = 2S\left(\frac{m}{2}\right) + m$ Case 2!

Let $S(m) = \Theta(m \log m)$ Substitute Back

Let $T(n) = \Theta(\log n \log \log n)$

Tree method

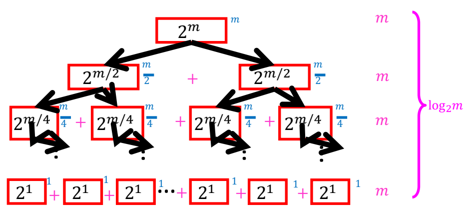
$n = 2^m$ $\quad T(2^m) = 2T\left(2^{\frac{m}{2}}\right) + m$



13

Tree method

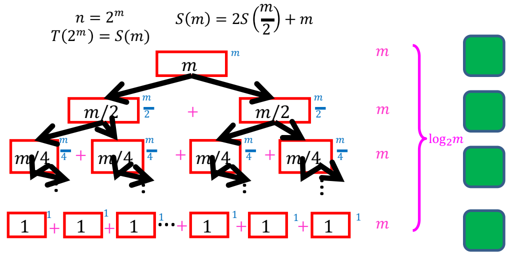
$n = 2^m$ $\quad T(2^m) = 2T(2^{m/2}) + m$



14

Tree method

$n = 2^m$
$T(2^m) = S(m)$ $\quad S(m) = 2S\left(\frac{m}{2}\right) + m$



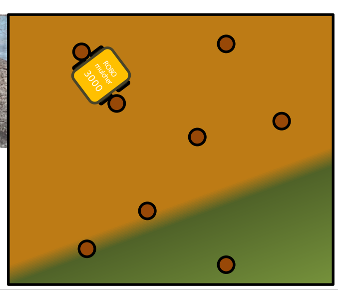
$T(n) = O(m \cdot \log_2 m) = O(\log_2 n \cdot \log_2 \log_2 n)$

15

My Yard

There has to be an easier way!

Constraints: Trees and Plants

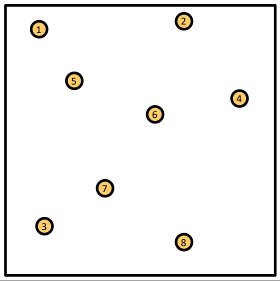


Need to find:
Closest Pair of Trees - how wide can the robot be?

Closest Pair of Points

Given:
A list of points

Return:
Pair of points with
smallest distance apart

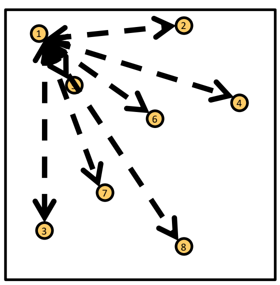


Closest Pair of Points: Naïve

Given:
A list of points

Return:
Pair of points with
smallest distance apart

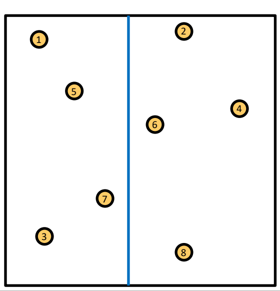
Algorithm: $O(n^2)$
Test every pair of points,
return the closest.



Closest Pair of Points: D&C

Divide: How?
At median x coordinate

Conquer:

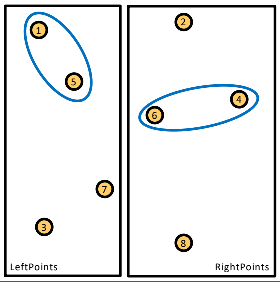


Closest Pair of Points: D&C

Divide:
At median x coordinate

Conquer:
Recursively find closest pairs from Left and Right

Combine:



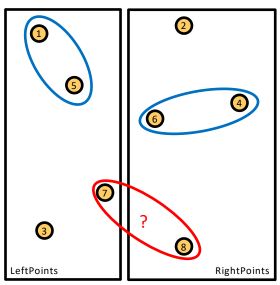
22

Closest Pair of Points: D&C

Divide:
At median x coordinate

Conquer:
Recursively find closest pairs from Left and Right

Combine:
Return min of Left and Right pairs Problem?



23

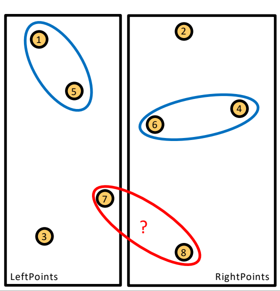
Closest Pair of Points: D&C

Combine:
2 Cases:

1. Closest Pair is completely in Left or Right

2. Closest Pair Spans our “Cut”

Need to test points across the cut



24

Spanning the Cut

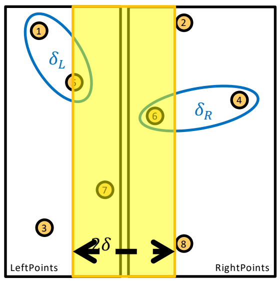
Combine:

2. Closest Pair Spanned our "Cut"

Need to test points across the cut

Compare all points within $\delta = \min\{\delta_L, \delta_R\}$ of the cut.

How many are there?



25

Spanning the Cut

Combine:

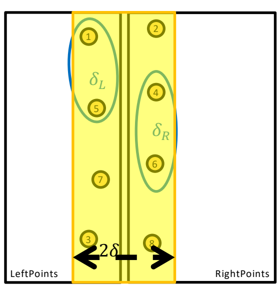
2. Closest Pair Spanned our "Cut"

Need to test points across the cut

Compare all points within $\delta = \min\{\delta_L, \delta_R\}$ of the cut.

How many are there?

$T(n) = 2T\left(\frac{n}{2}\right) + \left(\frac{n}{2}\right)^2 = \Theta(n^2)$



26

Spanning the Cut

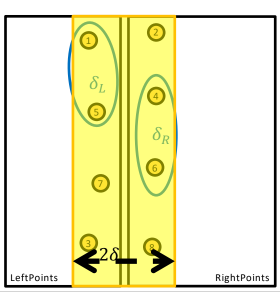
Combine:

2. Closest Pair Spanned our "Cut"

Need to test points across the cut

We don't need to test all pairs!

Only need to test points within δ of one another



27

Reducing Search Space

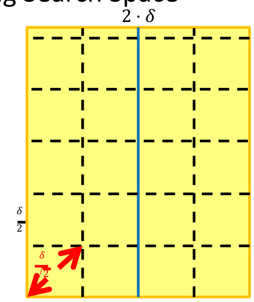
Combine:

2. Closest Pair Spanned our "Cut"

Need to test points across the cut

Divide the "runway" into square cubbies of size $\frac{\delta}{2}$

Each cubby will have at most 1 point!



28

Reducing Search Space

Combine:

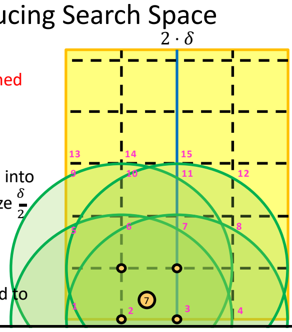
2. Closest Pair Spanned our "Cut"

Need to test points across the cut

Divide the "runway" into square cubbies of size $\frac{\delta}{2}$

How many cubbies could contain a point $< \delta$ away?

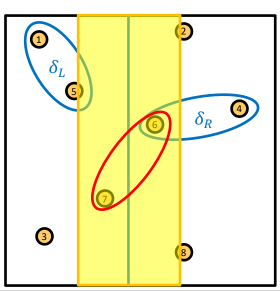
Each point compared to ≤ 15 other points



29

Closest Pair of Points: D&C

0. Sort points by x
1. Divide: At median x
2. Conquer: If >2 points Recursively find closest pair on left and right
3. Combine:
   a. List points in "runway" in order according to y value
   b. Compare each point to the next 15 above it, save best found
   c. Return min from left, right, and 3b



30

Listing points in "Runway"

- Given: y-sorted lists from left and right
- Return: y-sorted points in "runway"
- Target run time? $O(n)$

Left, sorted by y

3	7	5	1

Right, sorted by y

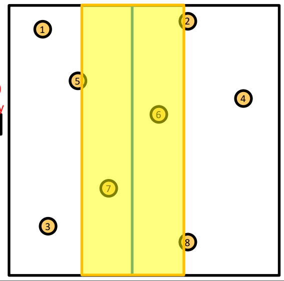
8	6	4	2

Merged, sorted by y

8	3	7	6	4	5	1	2

Runway, still sorted by y!

8	7	6	5	2



31

Run Time

0. Sort points by x — $\Theta(n \log n)$
1. Divide: At median x — $\Theta(1)$
2. Conquer: If >2 points, Recursively find closest pair on left and right — $T\left(\frac{n}{2}\right)$
3. Combine:
   a. Merge points to sort by y — $\Theta(n)$
   b. Compare each runway point to the next 15 runway points, save closest pair — $\Theta(n)$
   c. Return y-sorted points and min from left, right, and 3b — $\Theta(1)$

$T(n) = 2T\left(\frac{n}{2}\right) + \Theta(n)$

Case 2!

$T(n) = \Theta(n \log n)$

32