

# Chapter 5

## Divide and Conquer



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# Divide-and-Conquer

## Divide-and-conquer.

- Break up problem into several parts.
- Solve each part recursively.
- Combine solutions to sub-problems into overall solution.

## Most common usage.

- Break up problem of size  $n$  into **two** equal parts of size  $\frac{1}{2}n$ .
- Solve two parts recursively.
- Combine two solutions into overall solution in **linear time**.

## Consequence.

- Brute force:  $n^2$ .
- Divide-and-conquer:  $n \log n$ .

	$n$	$n \log_2 n$	$n^2$
$n = 10$	< 1 sec	< 1 sec	< 1 sec
$n = 30$	< 1 sec	< 1 sec	< 1 sec
$n = 50$	< 1 sec	< 1 sec	< 1 sec
$n = 100$	< 1 sec	< 1 sec	< 1 sec
$n = 1,000$	< 1 sec	< 1 sec	1 sec
$n = 10,000$	< 1 sec	< 1 sec	2 min
$n = 100,000$	< 1 sec	2 sec	3 hours
$n = 1,000,000$	1 sec	20 sec	12 days

# 5.1 Mergesort

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# Sorting

**Sorting.** Given  $n$  elements, rearrange in ascending order.

## Applications.

- Sort a list of names.
  - Organize an MP3 library.
  - Display Google PageRank results.
  - List RSS news items in reverse chronological order.
- obvious applications
- 
- Find the median.
  - Find the closest pair.
  - Binary search in a database.
  - Identify statistical outliers.
  - Find duplicates in a mailing list.
- problems become easy once items are in sorted order
- 
- Data compression.
  - Computer graphics.
  - Computational biology.
  - Supply chain management.
  - Book recommendations on Amazon.
  - Load balancing on a parallel computer.
  - ...
- non-obvious applications

# Mergesort

## Mergesort.

- Divide array into two halves.
- Recursively sort each half.
- Merge two halves to make sorted whole.



Jon von Neumann (1945)

A	L	G	O	R	I	T	H	M	S
---	---	---	---	---	---	---	---	---	---

A	L	G	O	R
---	---	---	---	---

I	T	H	M	S
---	---	---	---	---

divide  $O(1)$

A	G	L	O	R
---	---	---	---	---

H	I	M	S	T
---	---	---	---	---

sort  $2T(n/2)$

A	G	H	I	L	M	O	R	S	T
---	---	---	---	---	---	---	---	---	---

merge  $O(n)$

# Merging

**Merging.** Combine two pre-sorted lists into a sorted whole.

**How to merge efficiently?**



- Linear number of comparisons.
- Use temporary array.



**Challenge for the bored.** In-place merge. [Kronrud, 1969]

↑  
using only a constant amount of extra storage

# A Useful Recurrence Relation

**Def.**  $T(n)$  = number of comparisons to mergesort an input of size  $n$ .

**Mergesort recurrence.**

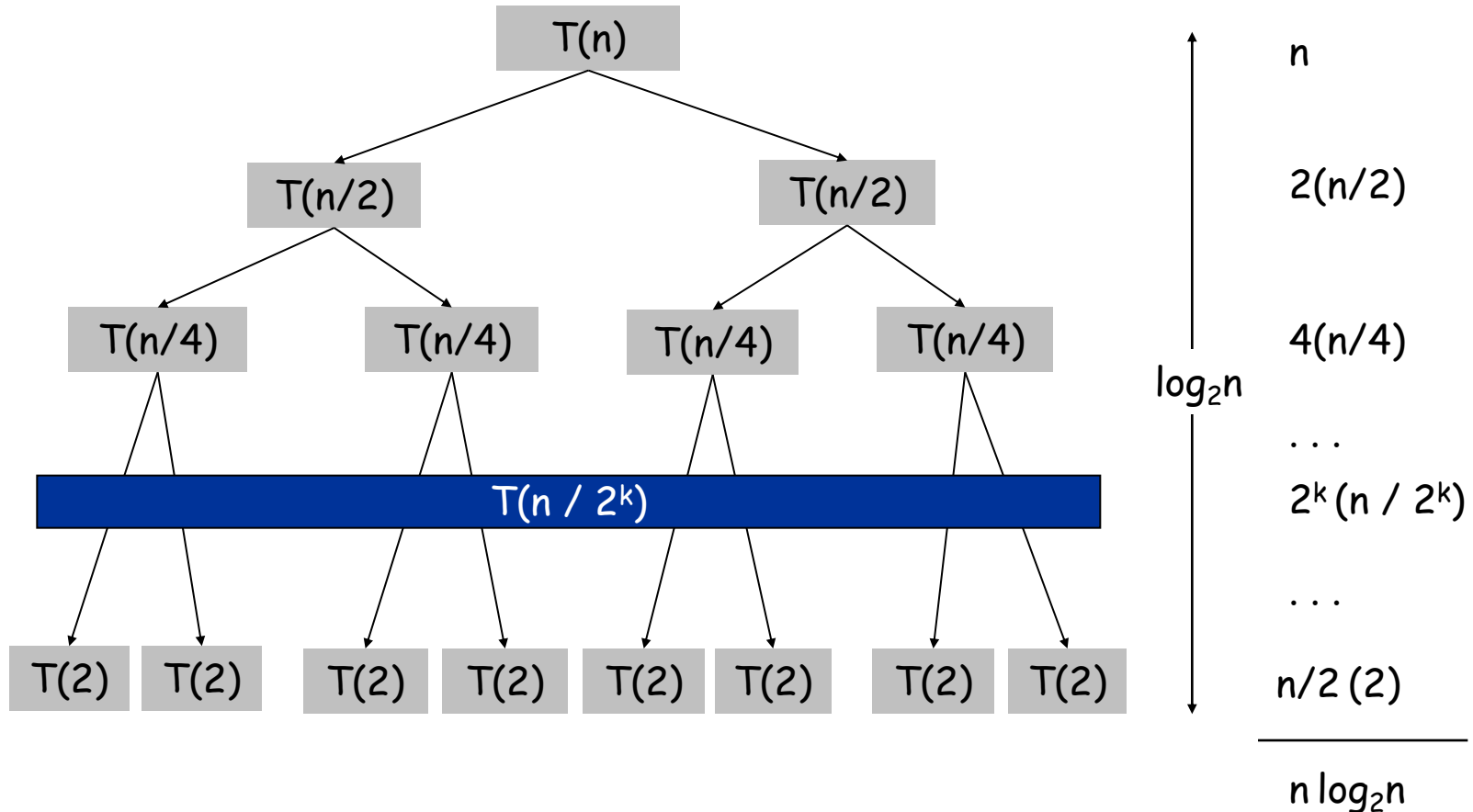
$$T(n) \leq \begin{cases} 0 & \text{if } n = 1 \\ \underbrace{T(\lceil n/2 \rceil)}_{\text{solve left half}} + \underbrace{T(\lfloor n/2 \rfloor)}_{\text{solve right half}} + \underbrace{n}_{\text{merging}} & \text{otherwise} \end{cases}$$

**Solution.**  $T(n) = O(n \log_2 n)$ .

**Assorted proofs.** We describe several ways to prove this recurrence. Initially we assume  $n$  is a power of 2 and replace  $\leq$  with  $=$ .

# Proof by Recursion Tree

$$T(n) = \begin{cases} 0 & \text{if } n=1 \\ \underbrace{2T(n/2)}_{\text{sorting both halves}} + \underbrace{n}_{\text{merging}} & \text{otherwise} \end{cases}$$





# Proof by Telescoping

**Claim.** If  $T(n)$  satisfies this recurrence, then  $T(n) = n \log_2 n$ .

↑  
assumes  $n$  is a power of 2

$$T(n) = \begin{cases} 0 & \text{if } n = 1 \\ \underbrace{2T(n/2)}_{\text{sorting both halves}} + \underbrace{n}_{\text{merging}} & \text{otherwise} \end{cases}$$

**Pf.** For  $n > 1$ :

$$\begin{aligned} \frac{T(n)}{n} &= \frac{2T(n/2)}{n} + 1 \\ &= \frac{T(n/2)}{n/2} + 1 \\ &= \frac{T(n/4)}{n/4} + 1 + 1 \\ &\dots \\ &= \frac{T(n/n)}{n/n} + \underbrace{1 + \dots + 1}_{\log_2 n} \\ &= \log_2 n \end{aligned}$$

# Proof by Induction

**Claim.** If  $T(n)$  satisfies this recurrence, then  $T(n) = n \log_2 n$ .

↑  
assumes  $n$  is a power of 2

$$T(n) = \begin{cases} 0 & \text{if } n = 1 \\ \underbrace{2T(n/2)}_{\text{sorting both halves}} + \underbrace{n}_{\text{merging}} & \text{otherwise} \end{cases}$$

**Pf.** (by induction on  $n$ )

- Base case:  $n = 1$ .
- Inductive hypothesis:  $T(n) = n \log_2 n$ .
- Goal: show that  $T(2n) = 2n \log_2 (2n)$ .

$$\begin{aligned} T(2n) &= 2T(n) + 2n \\ &= 2n \log_2 n + 2n \\ &= 2n(\log_2(2n) - 1) + 2n \\ &= 2n \log_2(2n) \end{aligned}$$

# Analysis of Mergesort Recurrence

**Claim.** If  $T(n)$  satisfies the following recurrence, then  $T(n) \leq n \lceil \lg n \rceil$ .

$$T(n) \leq \begin{cases} 0 & \text{if } n = 1 \\ \underbrace{T(\lceil n/2 \rceil)}_{\text{solve left half}} + \underbrace{T(\lfloor n/2 \rfloor)}_{\text{solve right half}} + \underbrace{n}_{\text{merging}} & \text{otherwise} \end{cases}$$

$\uparrow$   
 $\log_2 n$

**Pf.** (by induction on  $n$ )

- Base case:  $n = 1$ .
- Define  $n_1 = \lfloor n / 2 \rfloor$ ,  $n_2 = \lceil n / 2 \rceil$ .
- Induction step: assume true for  $1, 2, \dots, n-1$ .

$$\begin{aligned} T(n) &\leq T(n_1) + T(n_2) + n \\ &\leq n_1 \lceil \lg n_1 \rceil + n_2 \lceil \lg n_2 \rceil + n \\ &\leq n_1 \lceil \lg n_2 \rceil + n_2 \lceil \lg n_2 \rceil + n \\ &= n \lceil \lg n_2 \rceil + n \\ &\leq n(\lceil \lg n \rceil - 1) + n \\ &= n \lceil \lg n \rceil \end{aligned}$$

$$\begin{aligned} n_2 &= \lceil n/2 \rceil \\ &\leq \left\lceil 2^{\lceil \lg n \rceil} / 2 \right\rceil \\ &= 2^{\lceil \lg n \rceil} / 2 \\ \Rightarrow \lg n_2 &\leq \lceil \lg n \rceil - 1 \end{aligned}$$

## 5.3 Counting Inversions

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# Counting Inversions

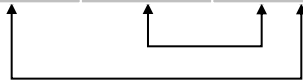
Music site tries to match your song preferences with others.

- You rank  $n$  songs.
- Music site consults database to find people with **similar** tastes.

**Similarity metric:** number of inversions between two rankings.

- My rank:  $1, 2, \dots, n$ .
- Your rank:  $a_1, a_2, \dots, a_n$ .
- Songs  $i$  and  $j$  **inverted** if  $i < j$ , but  $a_i > a_j$ .

Songs					
	A	B	C	D	E
Me	1	2	3	4	5
You	1	3	4	2	5



Inversions

3-2, 4-2

**Brute force:** check all  $\Theta(n^2)$  pairs  $i$  and  $j$ .

# Applications

## Applications.

- Voting theory.
- Collaborative filtering.
- Measuring the "sortedness" of an array.
- Sensitivity analysis of Google's ranking function.
- Rank aggregation for meta-searching on the Web.
- Nonparametric statistics (e.g., Kendall's Tau distance).

# Counting Inversions: Divide-and-Conquer

Divide-and-conquer.

1	5	4	8	10	2	6	9	12	11	3	7
---	---	---	---	----	---	---	---	----	----	---	---

# Counting Inversions: Divide-and-Conquer

Divide-and-conquer.

- **Divide**: separate list into two pieces.

1	5	4	8	10	2	6	9	12	11	3	7
---	---	---	---	----	---	---	---	----	----	---	---

Divide:  $O(1)$ .

1	5	4	8	10	2	6	9	12	11	3	7
---	---	---	---	----	---	---	---	----	----	---	---



# Counting Inversions: Divide-and-Conquer

## Divide-and-conquer.

- Divide: separate list into two pieces.
- **Conquer**: recursively count inversions in each half.

1	5	4	8	10	2	6	9	12	11	3	7
---	---	---	---	----	---	---	---	----	----	---	---

Divide:  $O(1)$ .

1	5	4	8	10	2	6	9	12	11	3	7
---	---	---	---	----	---	---	---	----	----	---	---

Conquer:  $2T(n / 2)$

5 blue-blue inversions

8 green-green inversions

5-4, 5-2, 4-2, 8-2, 10-2

6-3, 9-3, 9-7, 12-3, 12-7, 12-11, 11-3, 11-7

# Counting Inversions: Divide-and-Conquer

## Divide-and-conquer.

- Divide: separate list into two pieces.
- Conquer: recursively count inversions in each half.
- **Combine**: count inversions where  $a_i$  and  $a_j$  are in different halves, and return sum of three quantities.

1	5	4	8	10	2	6	9	12	11	3	7
---	---	---	---	----	---	---	---	----	----	---	---

Divide:  $O(1)$ .

1	5	4	8	10	2	6	9	12	11	3	7
---	---	---	---	----	---	---	---	----	----	---	---

5 blue-blue inversions

8 green-green inversions

Conquer:  $2T(n / 2)$

9 blue-green inversions

5-3, 4-3, 8-6, 8-3, 8-7, 10-6, 10-9, 10-3, 10-7

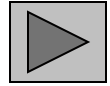
**Combine**: ???

Total =  $5 + 8 + 9 = 22$ .

# Counting Inversions: Combine

**Combine:** count blue-green inversions

- Assume each half is **sorted**.
- Count inversions where  $a_i$  and  $a_j$  are in different halves.
- **Merge** two sorted halves into sorted whole.



to maintain sorted invariant

3	7	10	14	18	19
---	---	----	----	----	----

2	11	16	17	23	25
6	3	2	2	0	0

13 blue-green inversions:  $6 + 3 + 2 + 2 + 0 + 0$

Count:  $O(n)$

2	3	7	10	11	14	16	17	18	19	23	25
---	---	---	----	----	----	----	----	----	----	----	----

Merge:  $O(n)$

$$T(n) \leq T(\lfloor n/2 \rfloor) + T(\lceil n/2 \rceil) + O(n) \Rightarrow T(n) = O(n \log n)$$

# Counting Inversions: Implementation

**Pre-condition.** [Merge-and-Count] A and B are sorted.

**Post-condition.** [Sort-and-Count] L is sorted.

```
Sort-and-Count(L) {  
    if list L has one element  
        return 0 and the list L  
  
    Divide the list into two halves A and B  
    ( $r_A$ , A)  $\leftarrow$  Sort-and-Count(A)  
    ( $r_B$ , B)  $\leftarrow$  Sort-and-Count(B)  
    ( $r$ , L)  $\leftarrow$  Merge-and-Count(A, B)  
  
    return  $r = r_A + r_B + r$  and the sorted list L  
}
```

## 5.4 Closest Pair of Points

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# Closest Pair of Points

**Closest pair.** Given  $n$  points in the plane, find a pair with smallest Euclidean distance between them.

**Fundamental geometric primitive.**

- Graphics, computer vision, geographic information systems, molecular modeling, air traffic control.
- Special case of nearest neighbor, Euclidean MST, Voronoi.

↑  
fast closest pair inspired fast algorithms for these problems

**Brute force.** Check all pairs of points  $p$  and  $q$  with  $\Theta(n^2)$  comparisons.

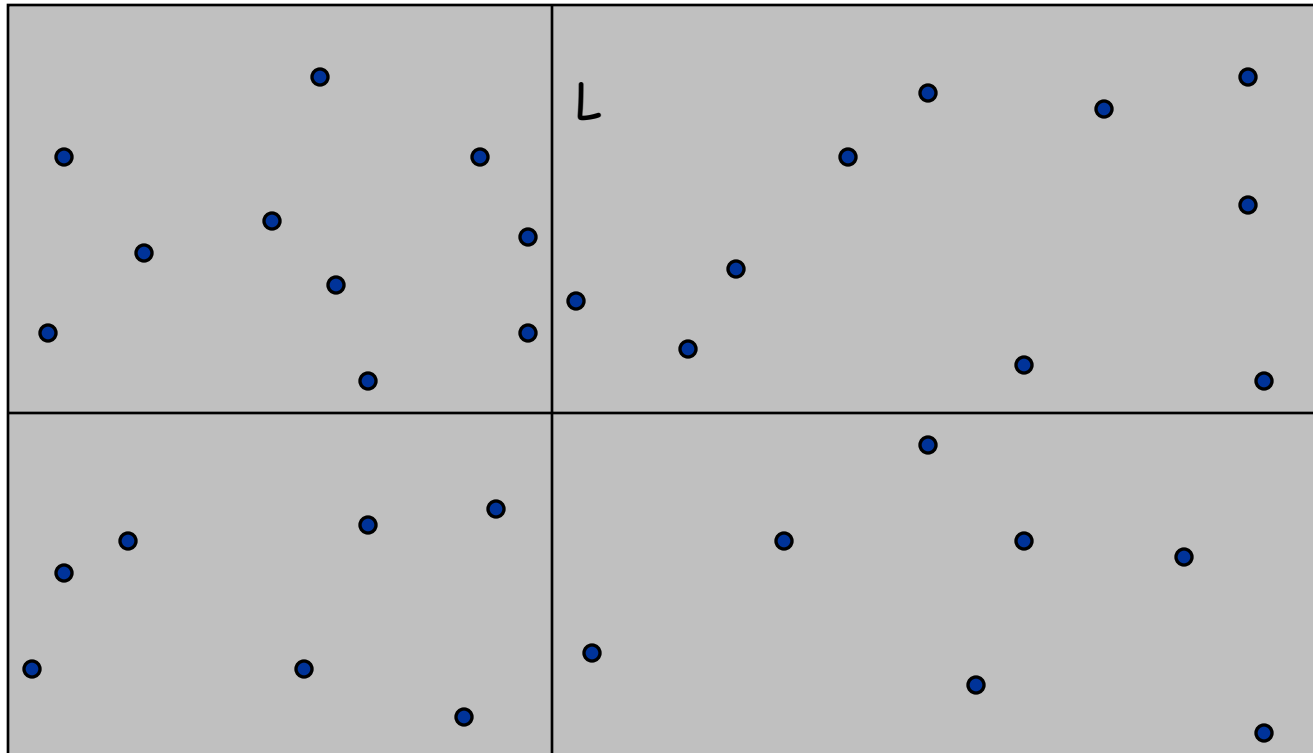
**1-D version.**  $O(n \log n)$  easy if points are on a line.

**Assumption.** No two points have the same  $x$  coordinate.

↑  
to make presentation cleaner

# Closest Pair of Points: First Attempt

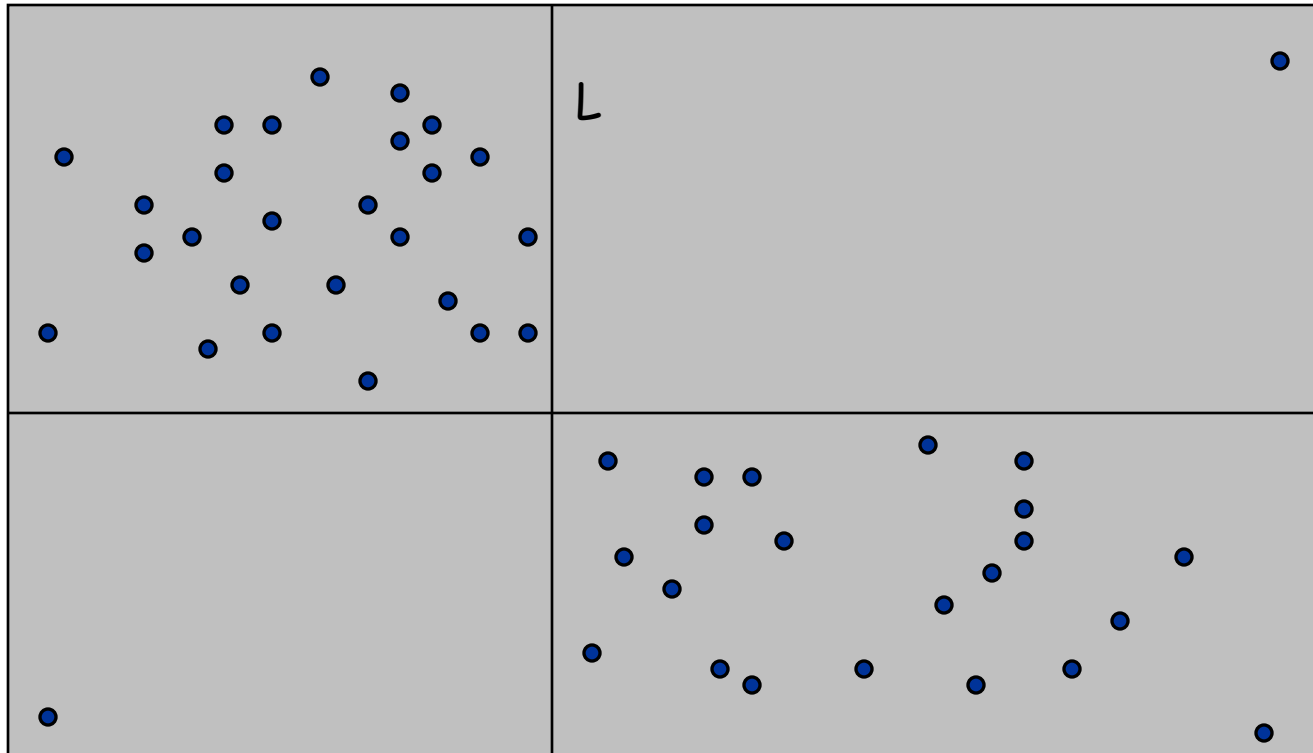
**Divide.** Sub-divide region into 4 quadrants.



## Closest Pair of Points: First Attempt

**Divide.** Sub-divide region into 4 quadrants.

**Obstacle.** Impossible to ensure  $n/4$  points in each piece.

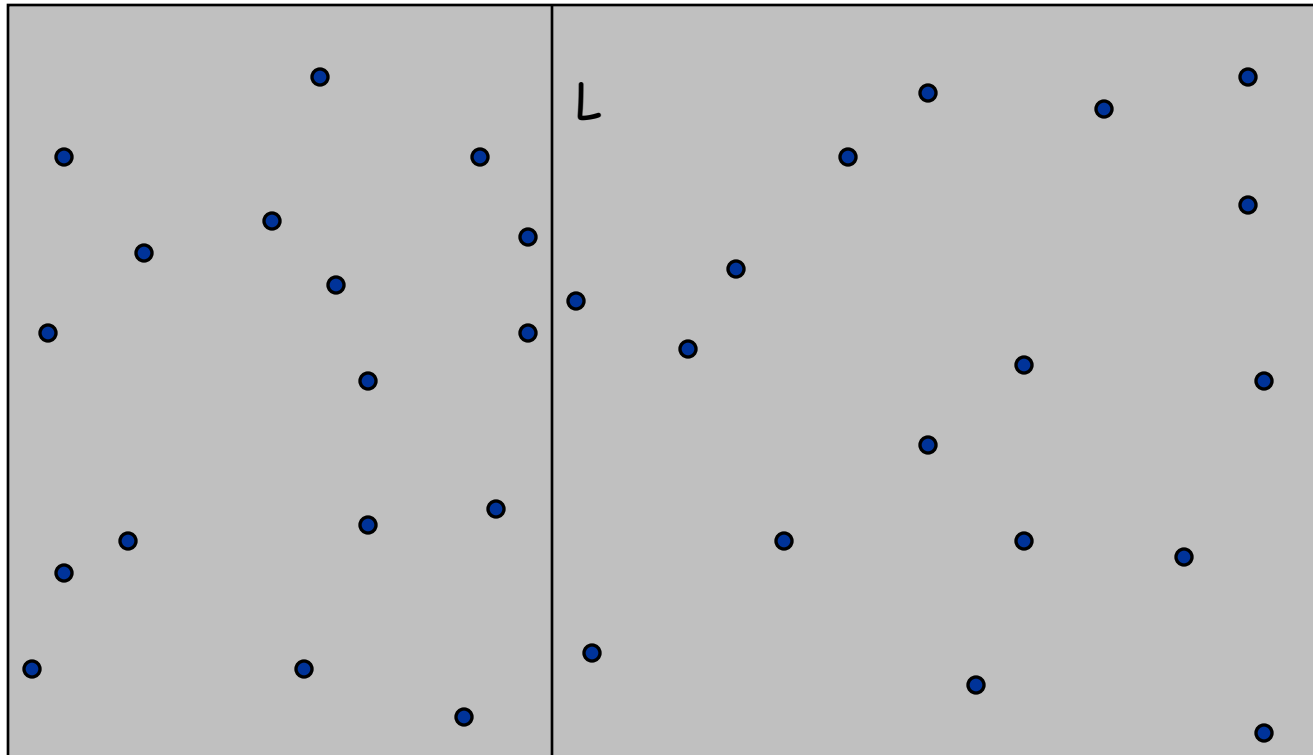




# Closest Pair of Points

## Algorithm.

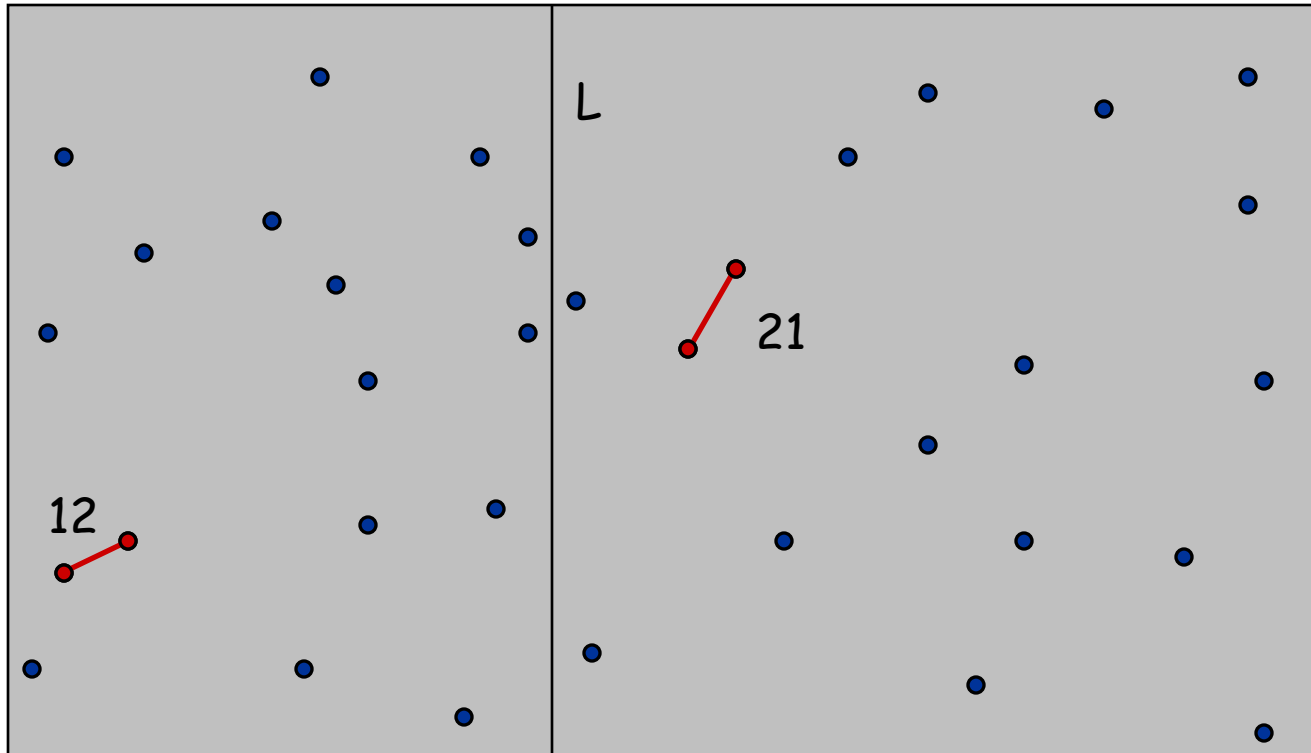
- **Divide:** draw vertical line  $L$  so that roughly  $\frac{1}{2}n$  points on each side.



# Closest Pair of Points

## Algorithm.

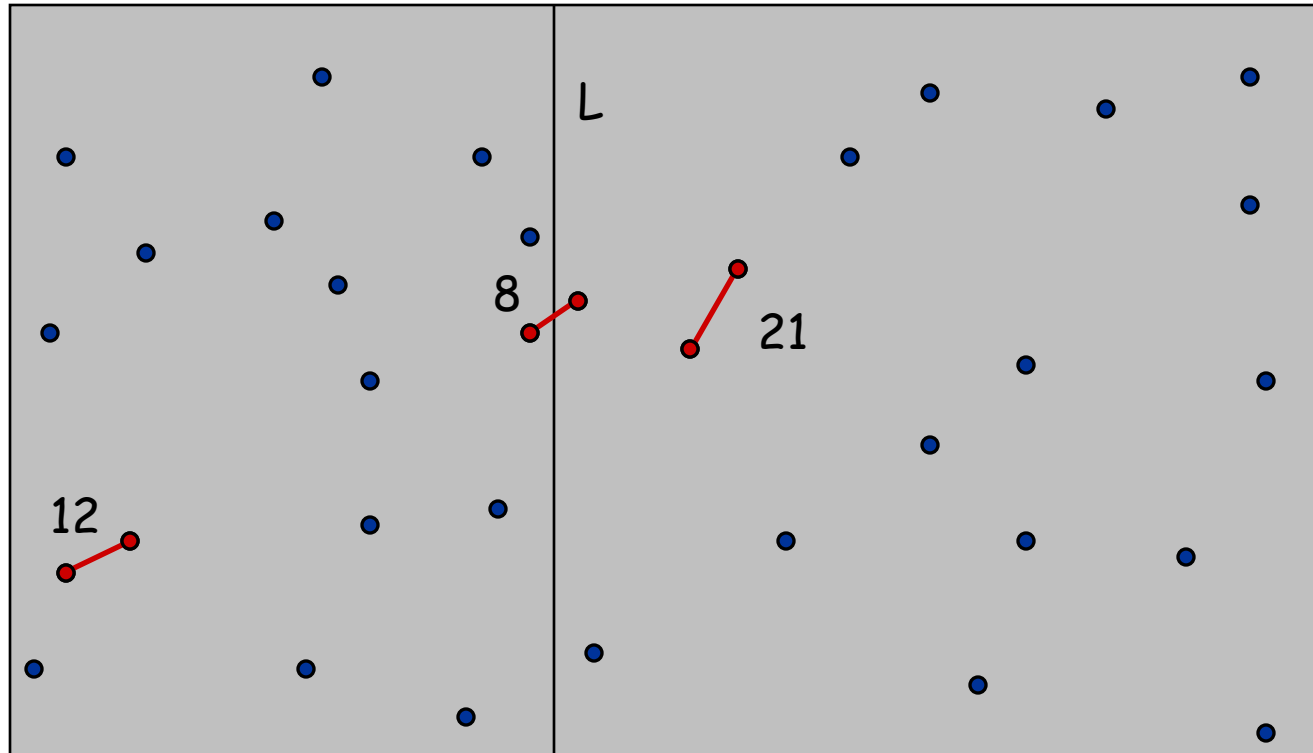
- Divide: draw vertical line  $L$  so that roughly  $\frac{1}{2}n$  points on each side.
- **Conquer**: find closest pair in each side recursively.



# Closest Pair of Points

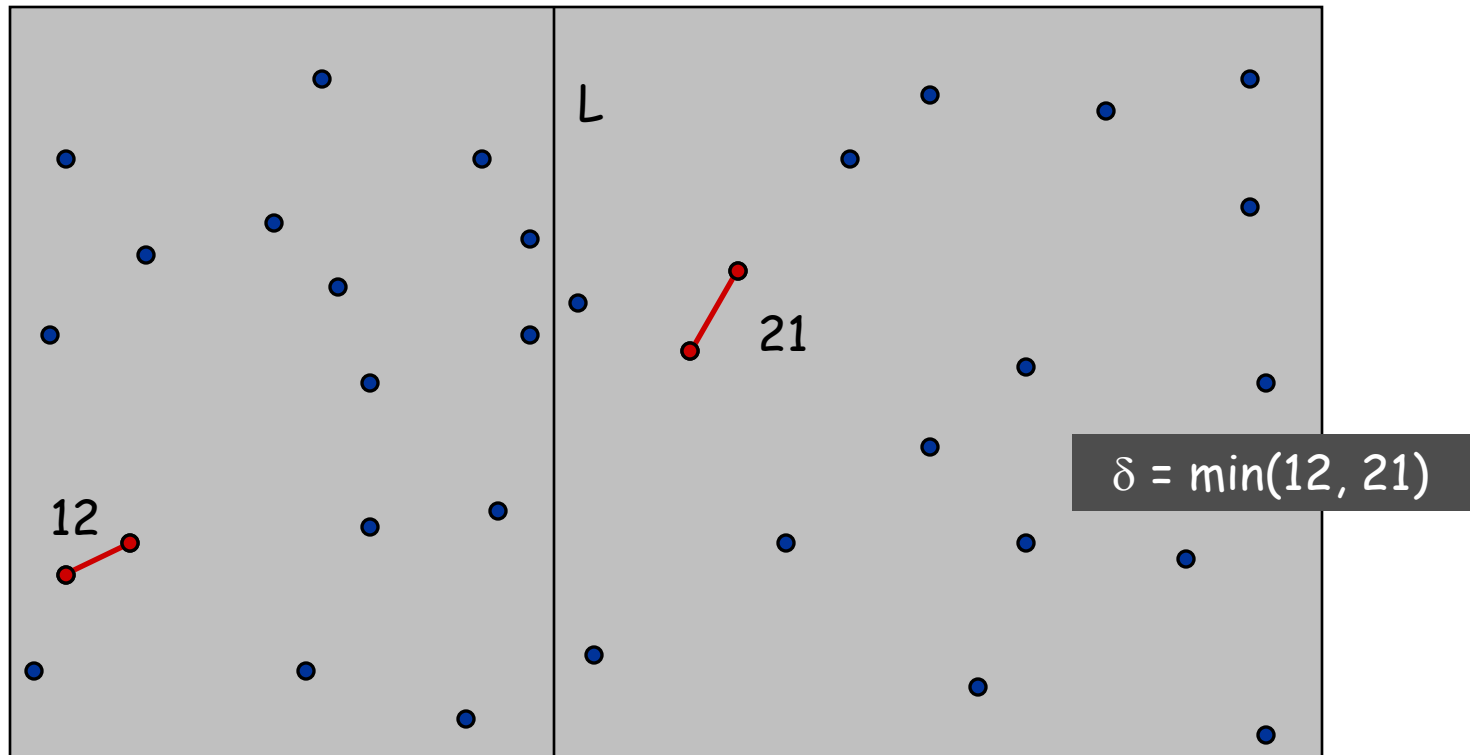
## Algorithm.

- Divide: draw vertical line  $L$  so that roughly  $\frac{1}{2}n$  points on each side.
- Conquer: find closest pair in each side recursively.
- **Combine**: find closest pair with one point in each side. ← seems like  $\Theta(n^2)$
- Return best of 3 solutions.



# Closest Pair of Points

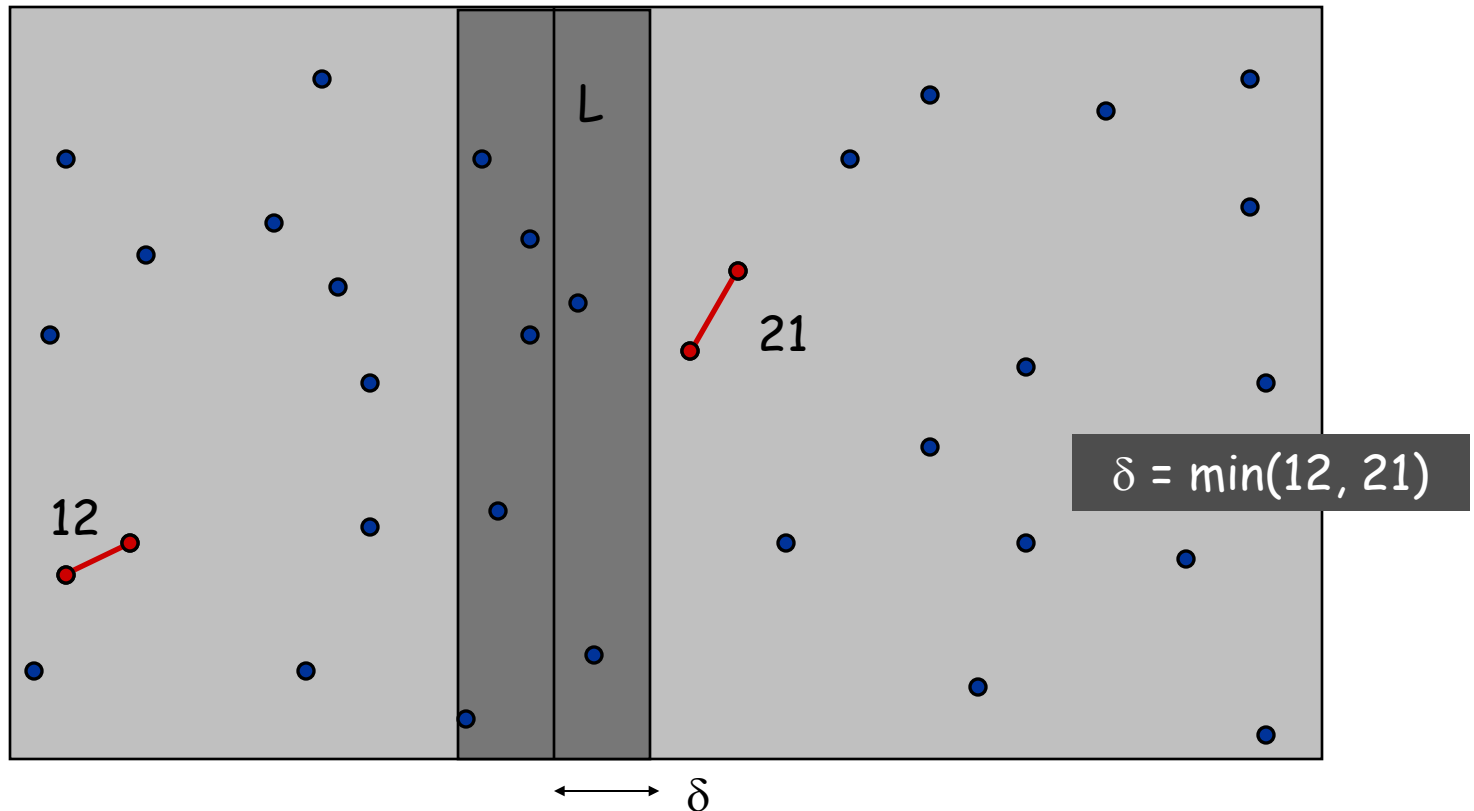
Find closest pair with one point in each side, **assuming that distance  $< \delta$** .



# Closest Pair of Points

Find closest pair with one point in each side, **assuming that distance  $< \delta$** .

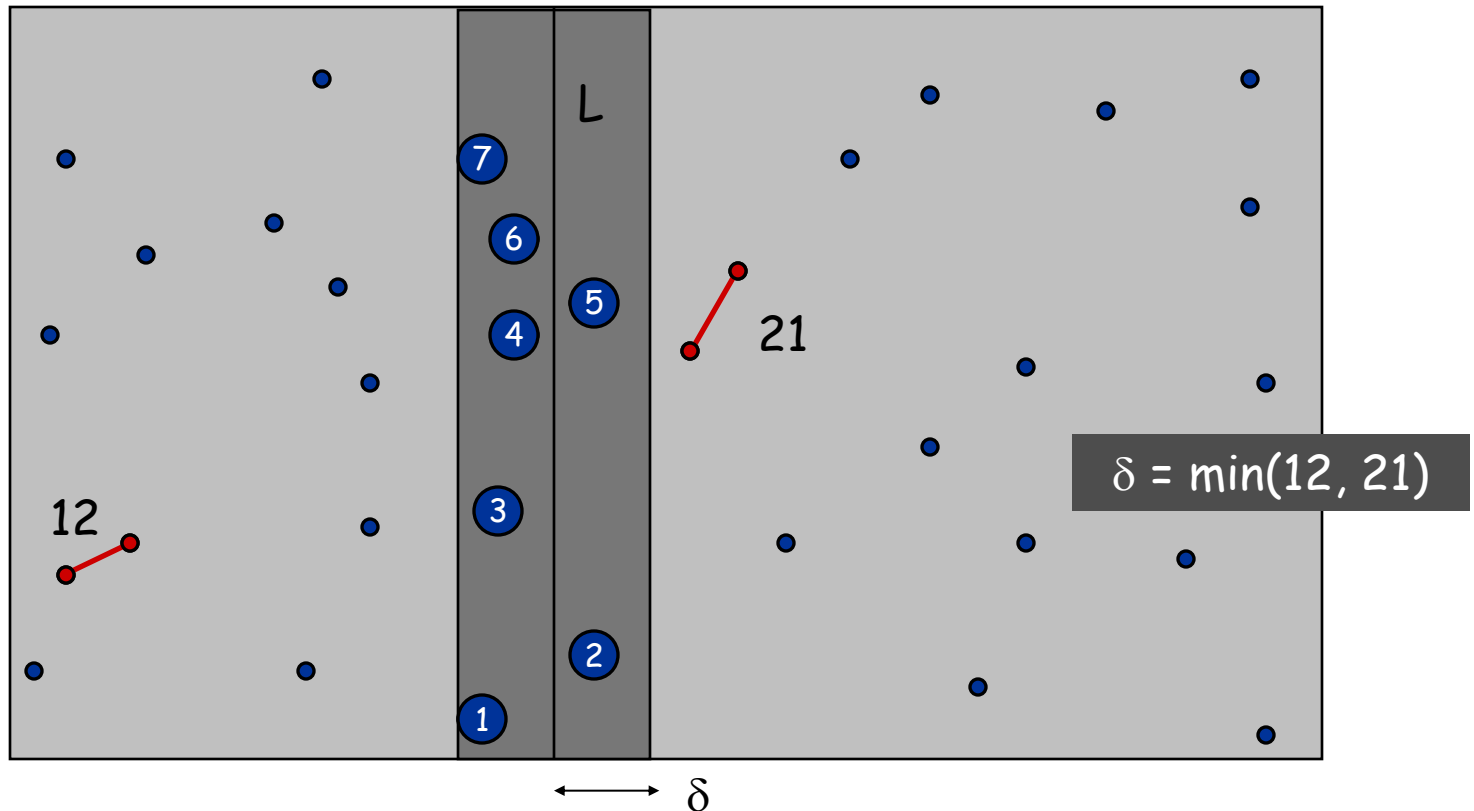
- Observation: only need to consider points within  $\delta$  of line  $L$ .



# Closest Pair of Points

Find closest pair with one point in each side, **assuming that distance  $< \delta$** .

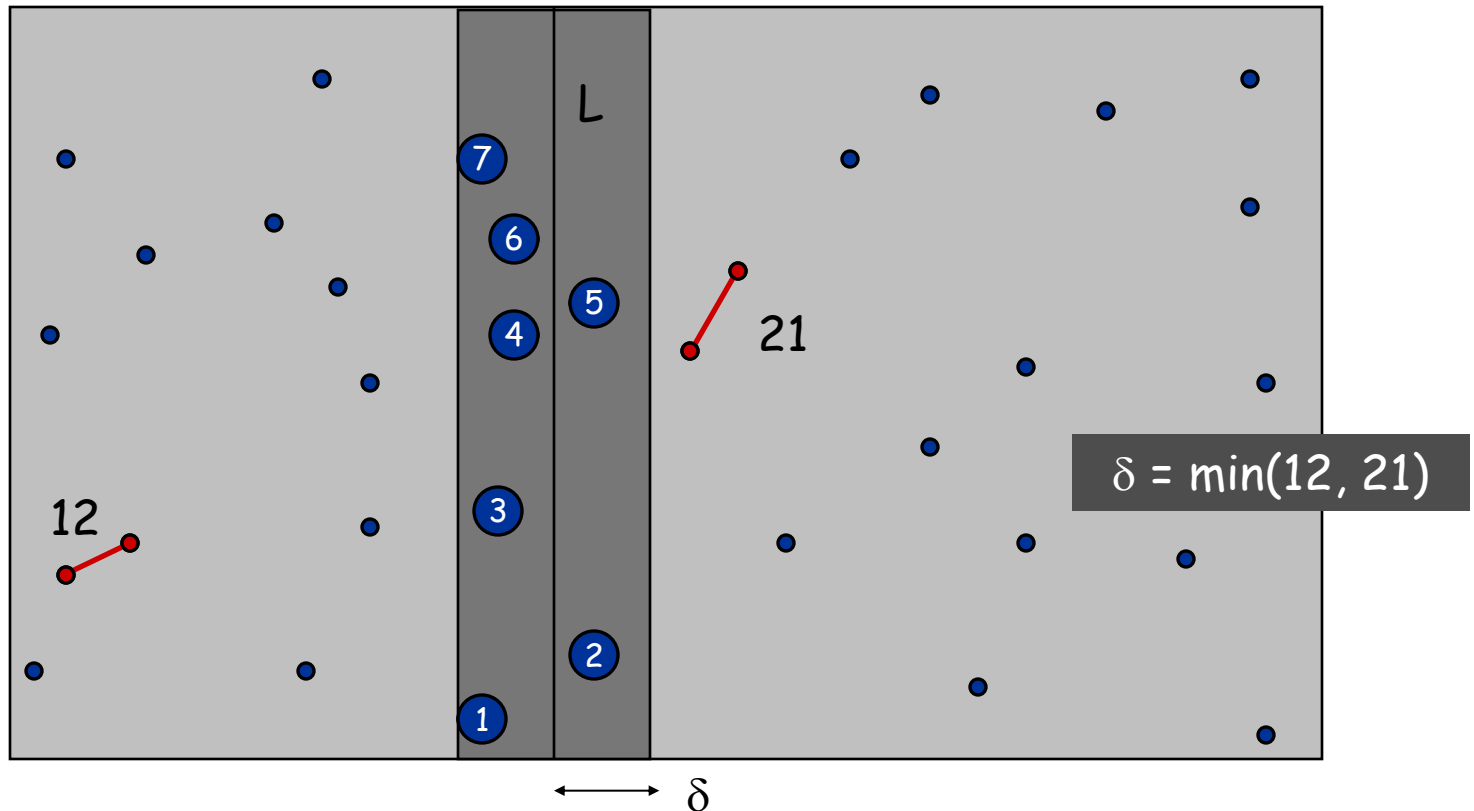
- Observation: only need to consider points within  $\delta$  of line  $L$ .
- Sort points in  $2\delta$ -strip by their  $y$  coordinate.



# Closest Pair of Points

Find closest pair with one point in each side, **assuming that distance  $< \delta$** .

- Observation: only need to consider points within  $\delta$  of line  $L$ .
- Sort points in  $2\delta$ -strip by their  $y$  coordinate.
- Only check distances of those within 11 positions in sorted list!



# Closest Pair of Points

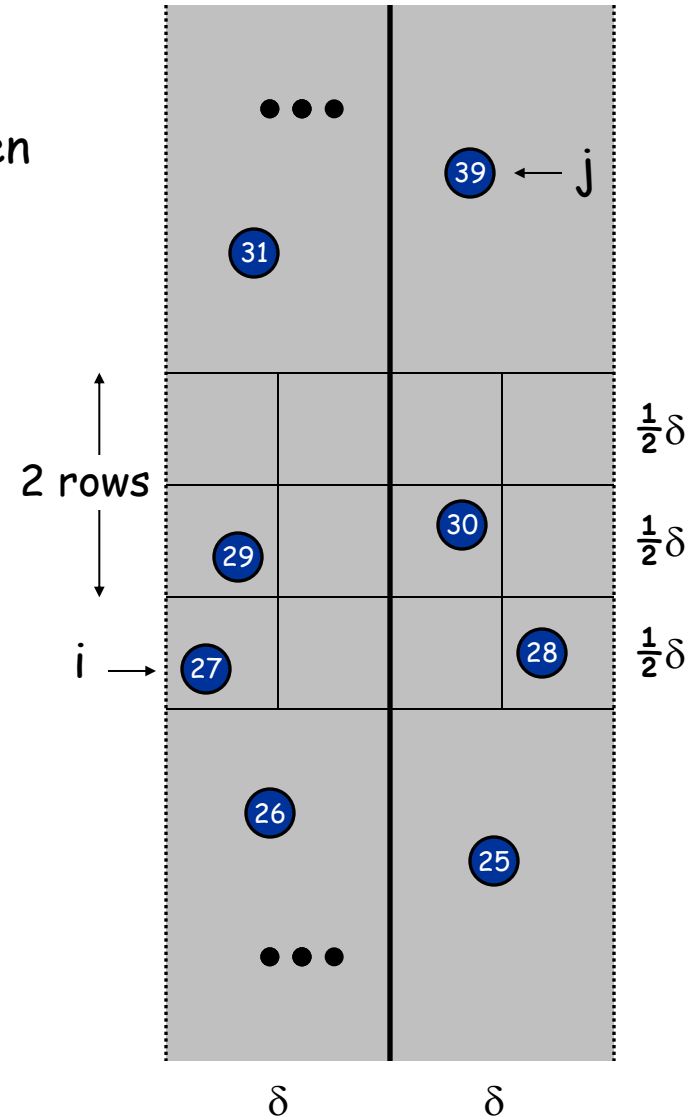
**Def.** Let  $s_i$  be the point in the  $2\delta$ -strip, with the  $i^{\text{th}}$  smallest  $y$ -coordinate.

**Claim.** If  $|i - j| > 11$ , then the distance between  $s_i$  and  $s_j$  is at least  $\delta$ .

**Pf.**

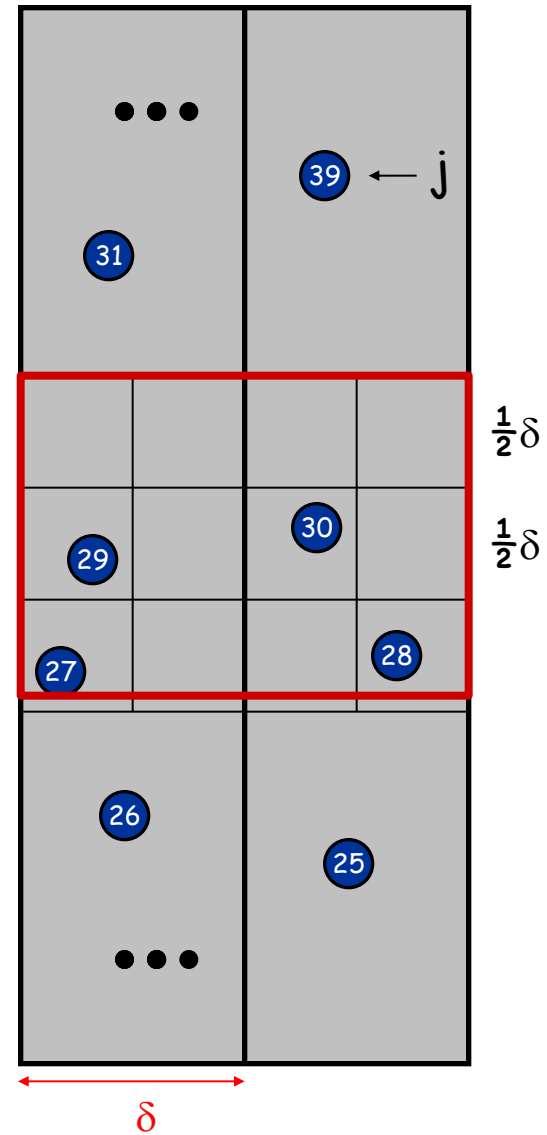
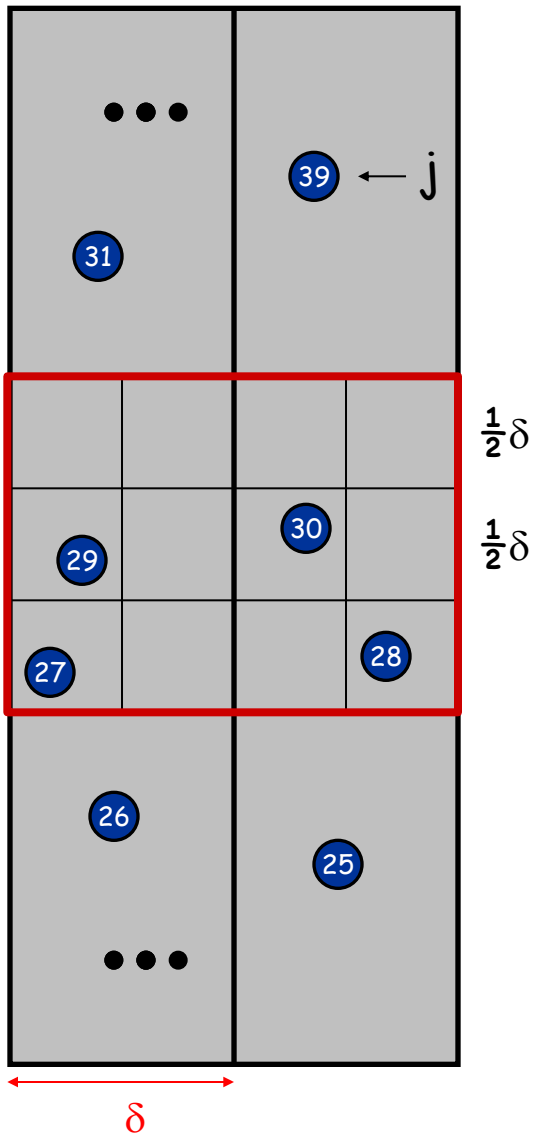
- No two points lie in same  $\frac{1}{2}\delta$ -by- $\frac{1}{2}\delta$  box.
- Two points at least 2 rows apart have distance  $\geq 2(\frac{1}{2}\delta)$ . ▪

**Fact.** Still true if we replace 11 with 7.

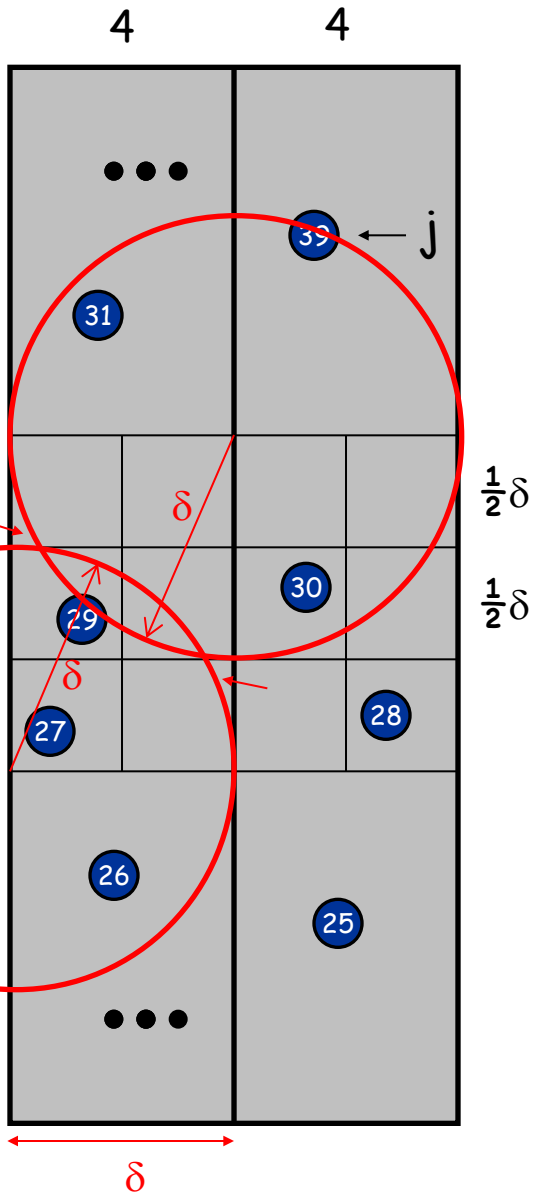




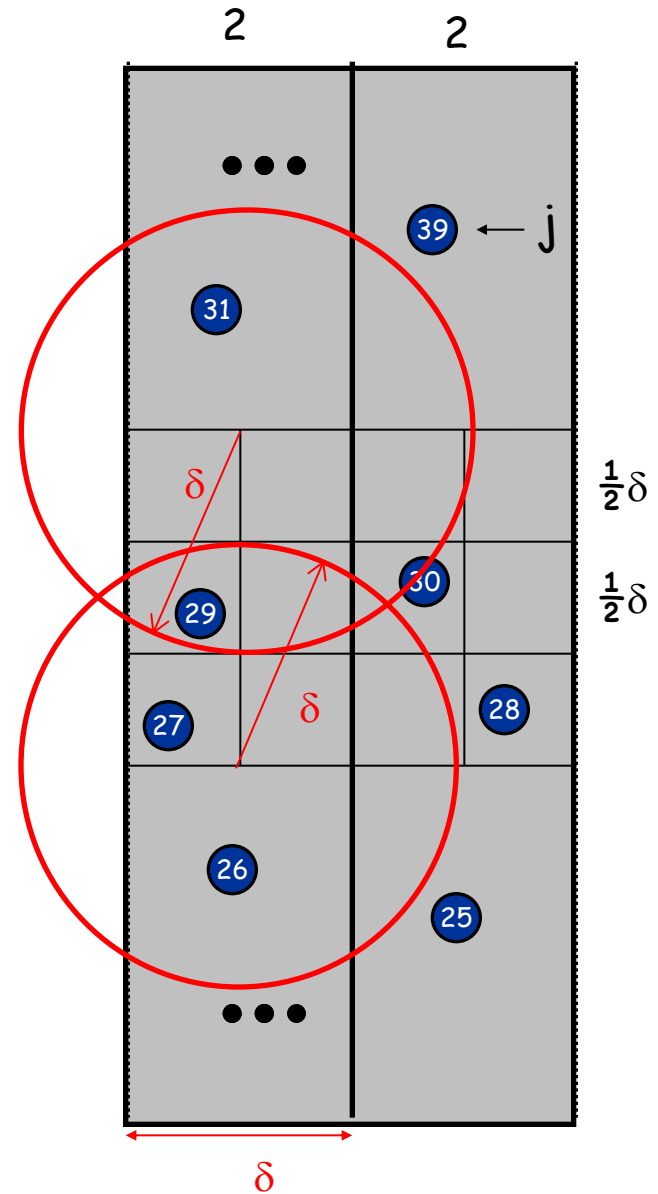
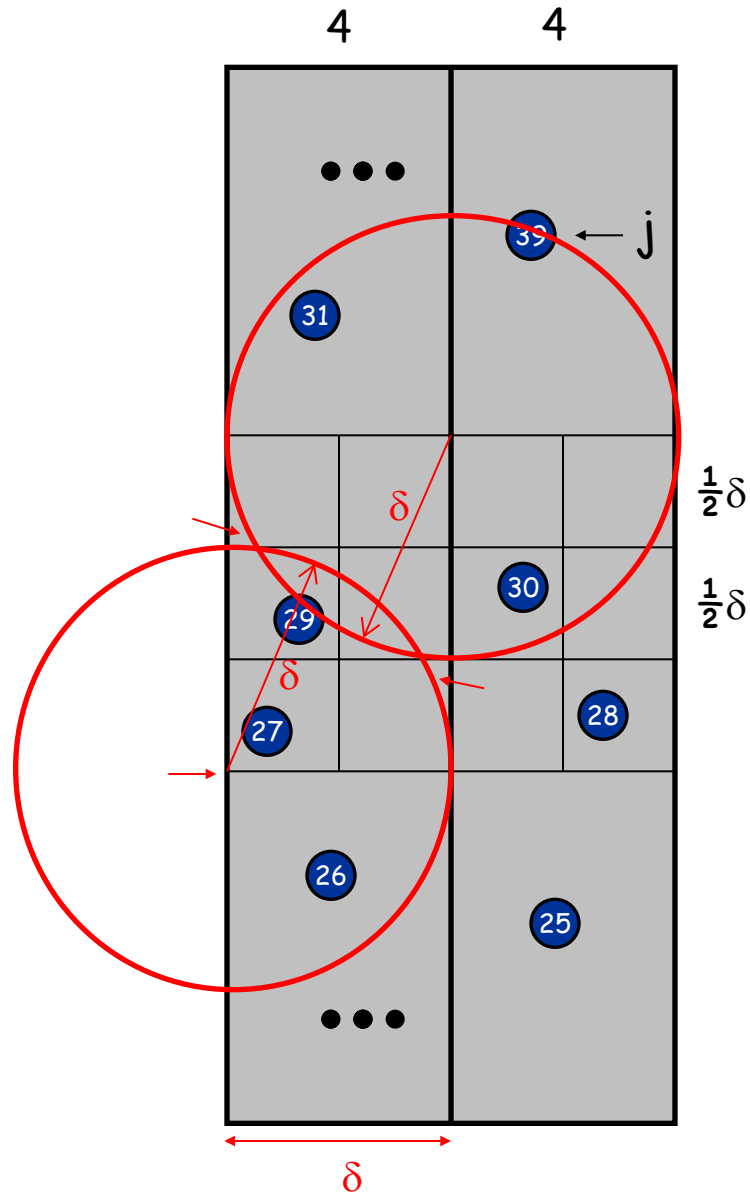
What is the maximum number of points we can place in this 3 rows area that each pairs of 2 points in either left and right side has distance larger than  $\delta$



What is the maximum number of points we can place in this 3 rows area that each pairs of 2 points in either left and right side has distance larger than  $\delta$



What is the maximum number of points we can place in this 3 rows area that each pairs of 2 points in either left and right side has distance larger than  $\delta$



# Closest Pair Algorithm

```
Closest-Pair( $p_1, \dots, p_n$ ) {  
  Compute separation line  $L$  such that half the points  
  are on one side and half on the other side.  $O(n \log n)$   
  
   $\delta_1 = \text{Closest-Pair}(\text{left half})$   $2T(n / 2)$   
   $\delta_2 = \text{Closest-Pair}(\text{right half})$   
   $\delta = \min(\delta_1, \delta_2)$   
  
  Delete all points further than  $\delta$  from separation line  $L$   $O(n)$   
  
  Sort remaining points sorted by  $y$ -coordinate.  $O(n \log n)$   
  
  Scan points in  $y$ -order and compare distance between  
  each point and next 11 neighbors. If any of these  
  distances is less than  $\delta$ , update  $\delta$ .  $O(n)$   
  
  return  $\delta$ .  
}
```

# Closest Pair of Points: Analysis

Running time.

$$T(n) \leq 2T(n/2) + O(n \log n) \Rightarrow T(n) = O(n \log^2 n)$$

Q. Can we achieve  $O(n \log n)$ ?

A. Yes. Don't sort points in strip from scratch each time.

- Each recursive returns two lists: all points sorted by y coordinate, and all points sorted by x coordinate.
- Sort by **merging** two pre-sorted lists.

$$T(n) \leq 2T(n/2) + O(n) \Rightarrow T(n) = O(n \log n)$$