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- Analogy: Mike is a student. ~~A student is Mike.~~

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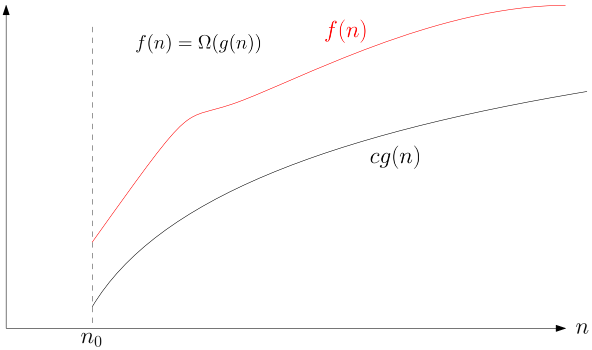

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Theorem $f(n) = O(g(n)) \Leftrightarrow g(n) = \Omega(f(n))$.

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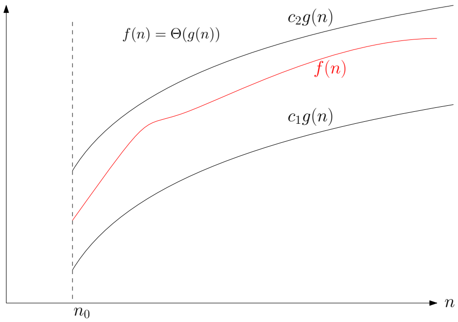

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Theorem $f(n) = \Theta(g(n))$ if and only if $f(n) = O(g(n))$ and $f(n) = \Omega(g(n))$.

Recall: O, Ω, Θ-Notation: Asymptotic Bounds

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$$f(n) = n^2$$

$$g(n) = \begin{cases} 1 & \text{if } n \text{ is odd} \\ n^3 & \text{if } n \text{ is even} \end{cases}$$

Recall: Informal way to define O-notation

- ignoring lower order terms: $3n^2 - 10n - 5 \to 3n^2$
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- $3n^2 - 10n - 5 = O(n^2)$ is the most natural since n^2 is the simplest term we can have inside $O(\cdot)$.

Notice that O denotes asymptotic upper bound

- $n^2 + 2n = O(n^3)$ is correct.
- The following sentence is correct: the running time of the insertion sort algorithm is $O(n^4)$.
- We say: the running time of the insertion sort algorithm is $O(n^2)$ and the bound is tight.

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- We do not use Ω and Θ very often when we upper bound running times.

Exercise

For each pair of functions f, g in the following table, indicate whether f is O, Ω or Θ of g.

f	g	O	Ω	Θ
$n^3 - 100n$	$5n^2 + 3n$			
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Questions?

Outline

$O(n)$ (Linear) Running Time

Computing the sum of n numbers

sum(A, n)

```
S ← 0
for i ← 1 to n
    S ← S + A[i]
return S
```

$O(n)$ (Linear) Running Time

- Merge two sorted arrays

3	8	12	20	32	48

5	7	9	25	29

$O(n)$ (Linear) Running Time

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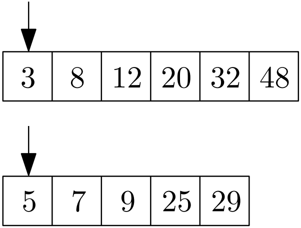

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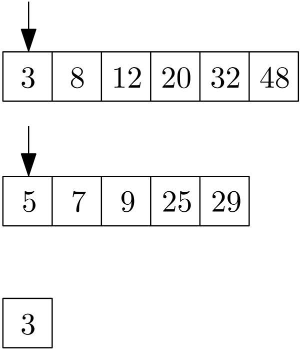

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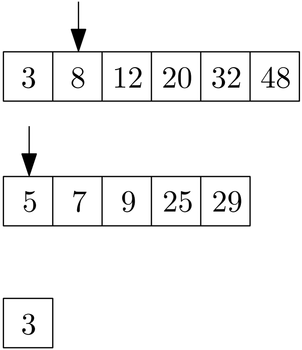

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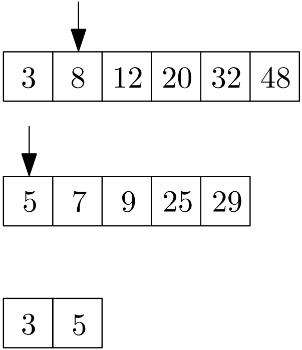

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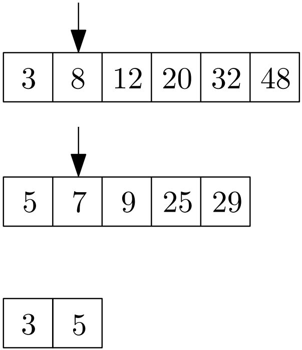

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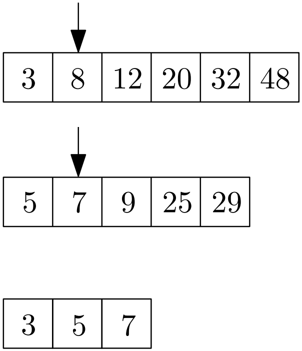

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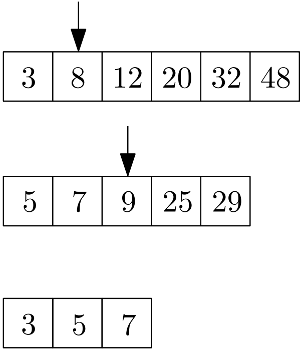

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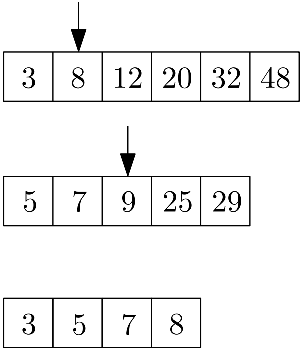

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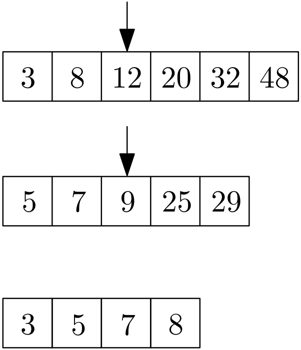

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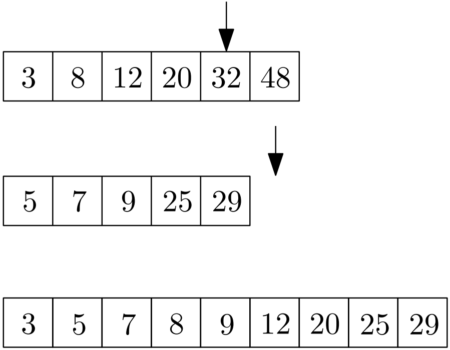

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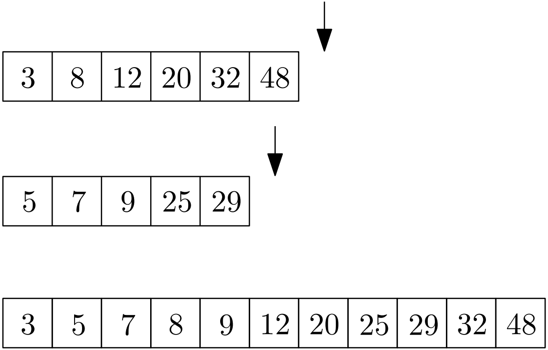


$O(n)$ (Linear) Running Time

merge(B, C, n_1, n_2) \\ B and C are sorted, with length n_1 and n_2

$A \leftarrow []$; $i \leftarrow 1$; $j \leftarrow 1$
while $i \leq n_1$ and $j \leq n_2$ **do**
  if $B[i] \leq C[j]$ **then**
    append $B[i]$ to A; $i \leftarrow i + 1$
  else
    append $C[j]$ to A; $j \leftarrow j + 1$
if $i \leq n_1$ then append $B[i..n_1]$ to A
if $j \leq n_2$ then append $C[j..n_2]$ to A
return A

$O(n)$ (Linear) Running Time

merge(B, C, n_1, n_2) \\ B and C are sorted, with length n_1 and n_2

```
A ← []; i ← 1; j ← 1
while i ≤ n1 and j ≤ n2 do
    if B[i] ≤ C[j] then
        append B[i] to A; i ← i + 1
    else
        append C[j] to A; j ← j + 1
if i ≤ n1 then append B[i..n1] to A
if j ≤ n2 then append C[j..n2] to A
return A
```

Running time $= O(n)$ where $n = n_1 + n_2$.

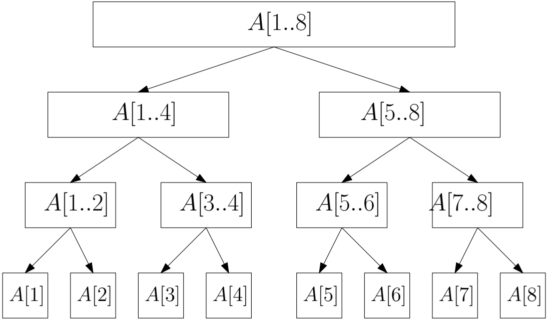
$O(n \log n)$ Running Time

merge-sort(A, n)

if $n = 1$ **then**
    return A
$B \leftarrow$ merge-sort$\left(A\left[1..\lfloor n/2 \rfloor\right], \lfloor n/2 \rfloor\right)$
$C \leftarrow$ merge-sort$\left(A\left[\lfloor n/2 \rfloor + 1..n\right], n - \lfloor n/2 \rfloor\right)$
return merge$(B, C, \lfloor n/2 \rfloor, n - \lfloor n/2 \rfloor)$

$O(n \log n)$ Running Time

- Merge-Sort



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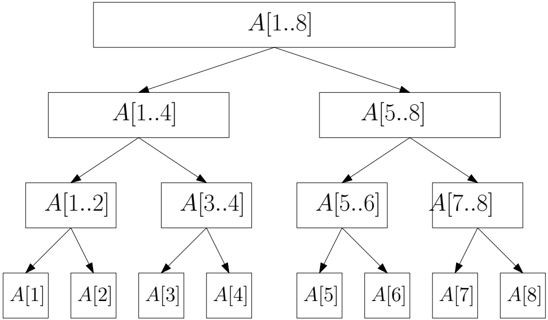

- Each level takes running time $O(n)$

$O(n \log n)$ Running Time

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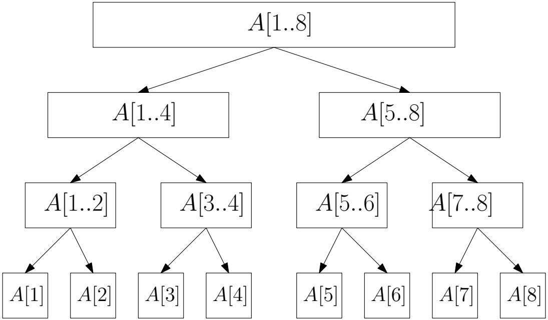
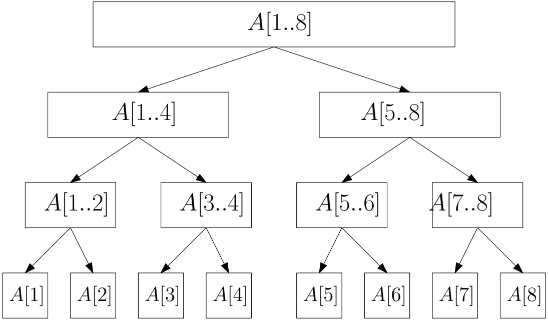


- Each level takes running time $O(n)$
- There are $O(\log n)$ levels

$O(n \log n)$ Running Time

- Merge-Sort



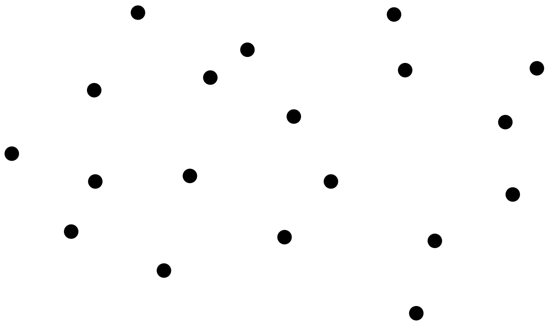
- Each level takes running time $O(n)$
- There are $O(\log n)$ levels
- Running time $= O(n \log n)$

$O(n^2)$ (Quardatic) Running Time

Closest Pair

Input: n points in plane: $(x_1, y_1), (x_2, y_2), \cdots, (x_n, y_n)$

Output: the pair of points that are closest



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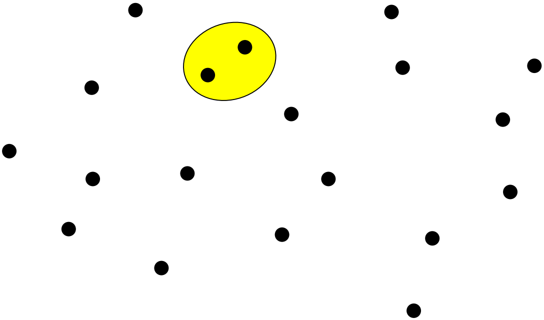

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Closest Pair

Input: n points in plane: $(x_1, y_1), (x_2, y_2), \cdots, (x_n, y_n)$

Output: the pair of points that are closest

closest-pair(x, y, n)

$bestd \leftarrow \infty$
for $i \leftarrow 1$ to $n - 1$ **do**
    for $j \leftarrow i + 1$ to n **do**
        $d \leftarrow \sqrt{(x[i] - x[j])^2 + (y[i] - y[j])^2}$
        if $d < bestd$ **then**
            $besti \leftarrow i, bestj \leftarrow j, bestd \leftarrow d$
return $(besti, bestj)$

$O(n^2)$ (Quardatic) Running Time

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closest-pair(x, y, n)

```
1: bestd ← ∞
2: for i ← 1 to n − 1 do
3:     for j ← i + 1 to n do
4:         d ← √((x[i] − x[j])² + (y[i] − y[j])²)
5:         if d < bestd then
6:             besti ← i, bestj ← j, bestd ← d
7: return (besti, bestj)
```

Closest pair can be solved in $O(n \log n)$ time!

$O(n^3)$ (Cubic) Running Time

Multiply two matrices of size $n \times n$

matrix-multiplication(A, B, n)

```
C ← matrix of size n × n, with all entries being 0
for i ← 1 to n do
    for j ← 1 to n do
        for k ← 1 to n do
            C[i, k] ← C[i, k] + A[i, j] × B[j, k]
return C
```

Beyond Polynomial Time: 2^n

Def. An independent set of a graph $G = (V, E)$ is a subset $S \subseteq V$ of vertices such that for every $u, v \in S$, we have $(u, v) \notin E$.

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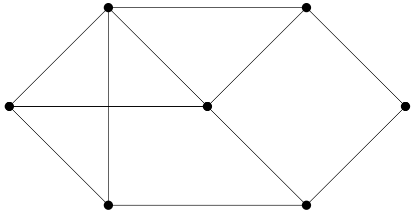

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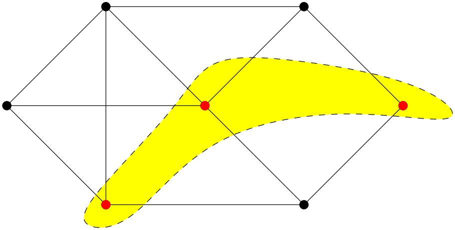

Beyond Polynomial Time: 2^n

Maximum Independent Set Problem

Input: graph $G = (V, E)$

Output: the maximum independent set of G

Beyond Polynomial Time: 2^n

Maximum Independent Set Problem

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max-independent-set($G = (V, E)$)

$R \leftarrow \emptyset$
for every set $S \subseteq V$ **do**
    $b \leftarrow$ true
    for every $u, v \in S$ **do**
        if $(u, v) \in E$ then $b \leftarrow$ false
    if b and $|S| > |R|$ then $R \leftarrow S$
return R

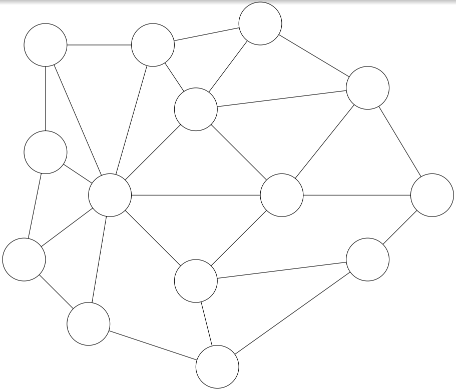
Running time $= O(2^n n^2)$.

Beyond Polynomial Time: $n!$

Hamiltonian Cycle Problem

Input: a graph with n vertices

Output: a cycle that visits each node exactly once, or say no such cycle exists



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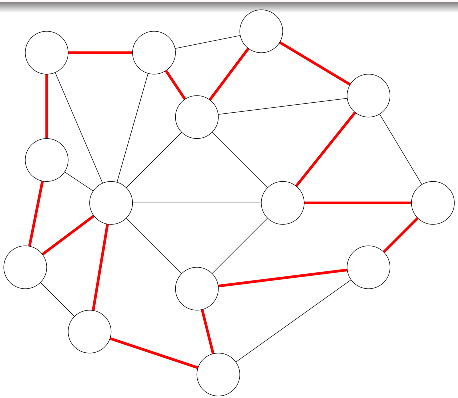

Beyond Polynomial Time: $n!$

Hamiltonian($G = (V, E)$)

for every permutation $(p_1, p_2, \cdots, p_n)$ of V **do**
    $b \leftarrow$ true
    for $i \leftarrow 1$ to $n - 1$ **do**
        if $(p_i, p_{i+1}) \notin E$ then $b \leftarrow$ false
    if $(p_n, p_1) \notin E$ then $b \leftarrow$ false
    if b then return $(p_1, p_2, \cdots, p_n)$
return "No Hamiltonian Cycle"

Running time $= O(n! \times n)$

$O(\log n)$ (Logarithmic) Running Time

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- Binary search
  - Input: sorted array A of size n, an integer t;
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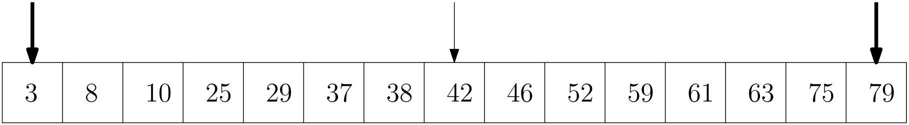

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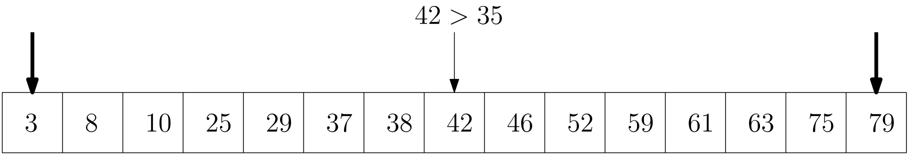

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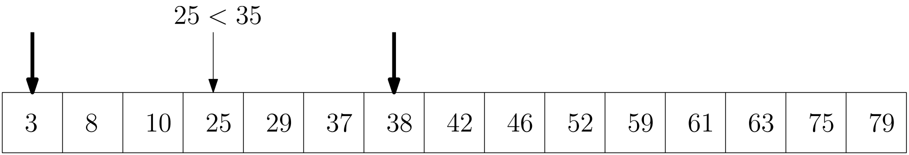

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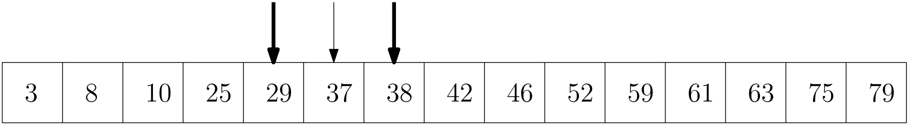

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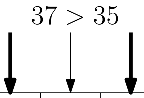

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Binary search

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binary-search(A, n, t)

```
i ← 1, j ← n
while i ≤ j do
    k ← ⌊(i + j)/2⌋
    if A[k] = t return true
    if t < A[k] then j ← k − 1 else i ← k + 1
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Running time $= O(\log n)$

Comparing the Orders

- Sort the functions from smallest to largest asymptotically
  $\log n, \;\; n \log n, \;\; n, \;\; n!, \;\; n^2, \;\; 2^n, \;\; e^n, \;\; n^n$
- $\log n = O(n)$

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- $n! = O(n^n)$

Terminologies

When we talk about upper bound on running time:

- Logarithmic time: $O(\log n)$
- Linear time: $O(n)$
- Quadratic time $O(n^2)$
- Cubic time $O(n^3)$
- Polynomial time: $O(n^k)$ for some constant k
  - $O(n \log n) \subseteq O(n^{1.1})$. So, an $O(n \log n)$-time algorithm is also a polynomial time algorithm.
- Exponential time: $O(c^n)$ for some $c > 1$
- Sub-linear time: $o(n)$
- Sub-quadratic time: $o(n^2)$