Algorithms: Recall Binary Search Trees and a Dynamic Programming

Theophile Thiery

EPFL School of Computer and Communication Sciences

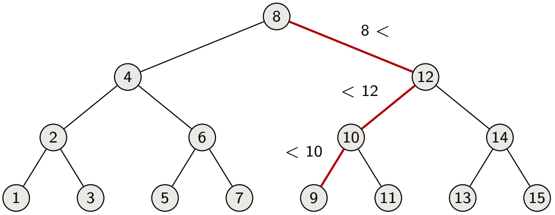
Lecture 9, 18.03.2025

RECALL BINARY SEARCH TREES

Binary Search Trees

Key property:

- If y is in the left subtree of x then $y.key < x.key$
- If y is in the right subtree of x then $y.key \geq x.key$



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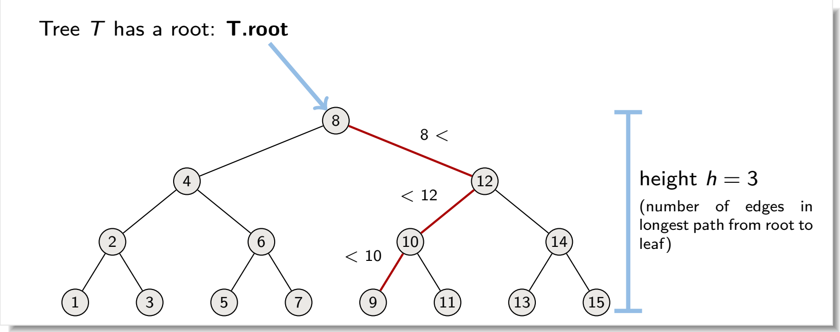

Binary Search Trees

Encodes a strategy whatever number we look for

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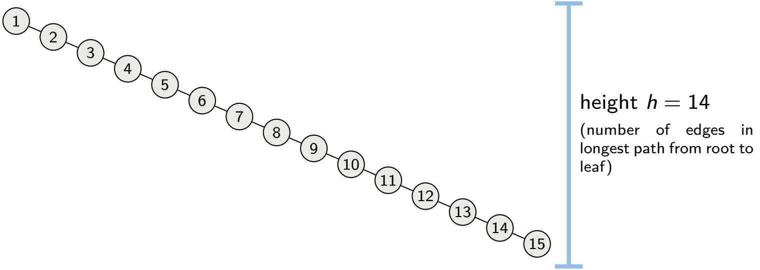
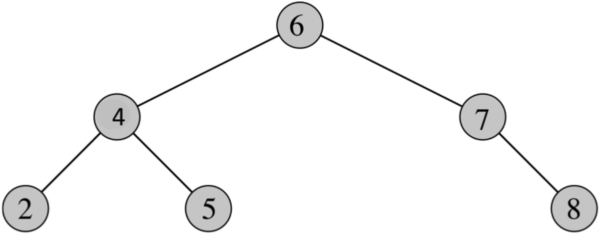


Basic operations take time proportional to height: $O(h)$

QUERYING A BINARY SEARCH TREE

(Searching, Minimum, Maximum, Successor, Predecessor)

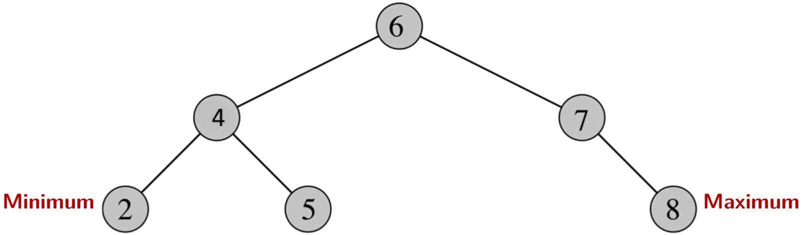
Searching



What is the running time? $O(h)$

```
TREE-SEARCH(x, k)
  if x == NIL or k == key[x]
      return x
  if k < x.key
      return TREE-SEARCH(x.left, k)
  else return TREE-SEARCH(x.right, k)
```

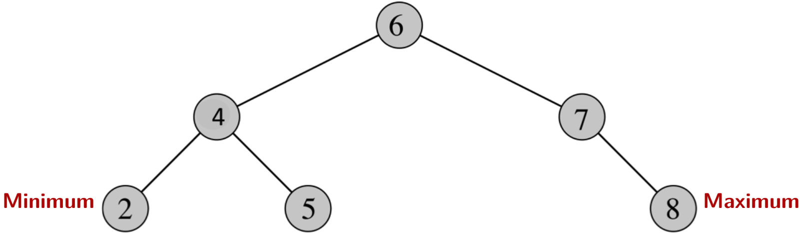
Minimum and Maximum



By key property:

- Minimum is located in leftmost node
- Maximum is located in rightmost node

Minimum and Maximum

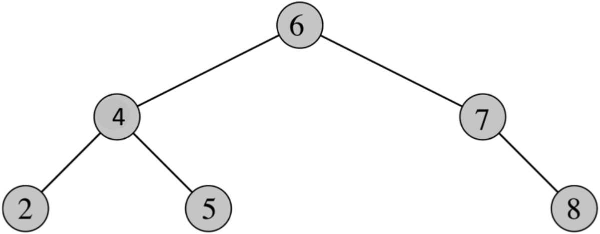


What is the running time? $O(h)$

```
TREE-MINIMUM(x)
  while x.left ≠ NIL
      x = x.left
  return x
```

```
TREE-MAXIMUM(x)
  while x.right ≠ NIL
      x = x.right
  return x
```

Successor



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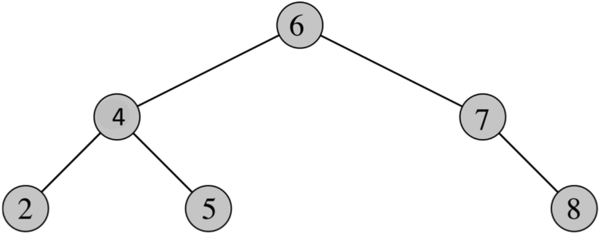
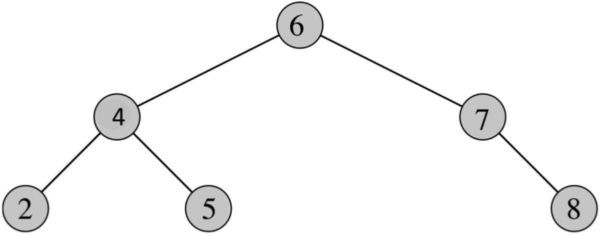


Successor of a node x is the node y such that $y.key$ is the

$$\text{"smallest key"} > x.key$$

Successor

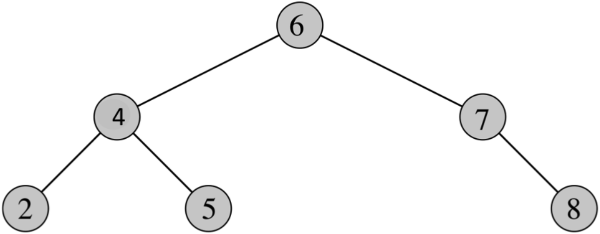


Successor of a node x is the node y such that $y.key$ is the

$$\text{“smallest key”} > x.key$$

- What is the successor of 6?

Successor



Successor of a node x is the node y such that $y.key$ is the

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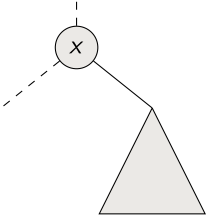
- What is the successor of 6?
- What is the successor of 5?

Two cases when finding successor of x:

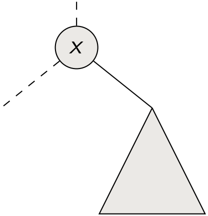
Case 1: x has a non-empty right subtree



Two cases when finding successor of x:

Case 1: x has a non-empty right subtree

x's successor is the minimum in the right subtree



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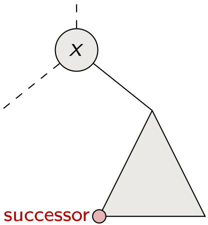

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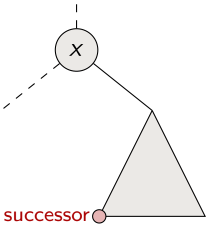
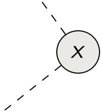


Case 2: x has an empty right subtree



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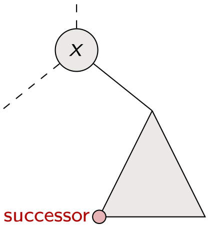
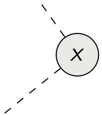


Case 2: x has an empty right subtree

As long as we go to the left up the tree we're visiting smaller keys

x's successor is y is the node that x is the predecessor of (x is the maximum in y's left subtree)



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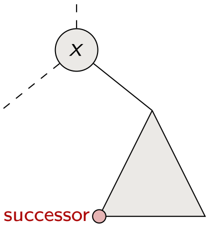

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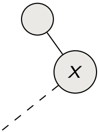

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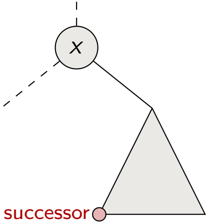

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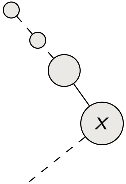

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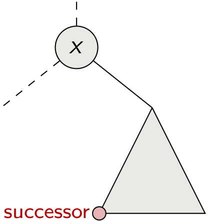

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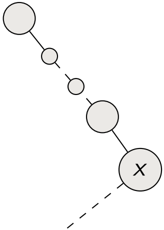

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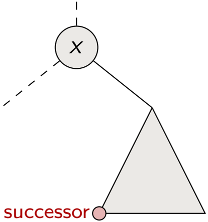

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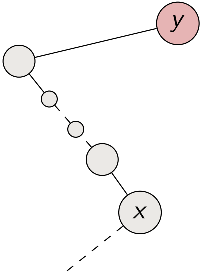
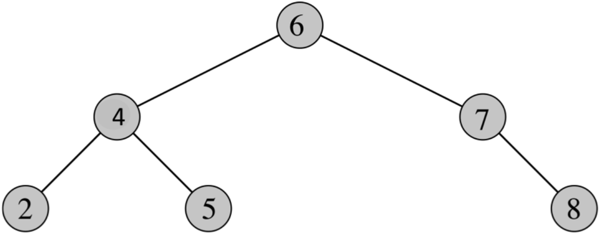


Successor (Predecessor is symmetric)



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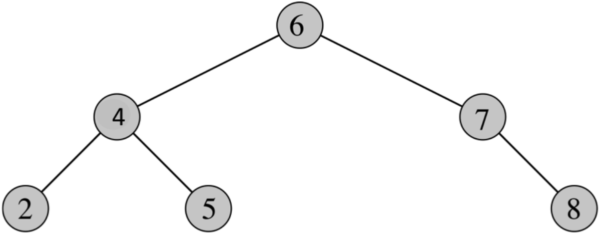


```
TREE-SUCCESSOR(x)
  if x.right ≠ NIL
      return TREE-MINIMUM(x.right)
  y = x.p
  while y ≠ NIL and x == y.right
      x = y
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  return y
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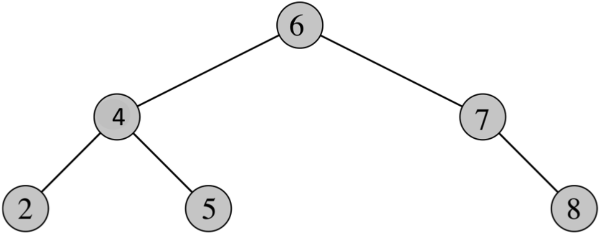

What is the running time?

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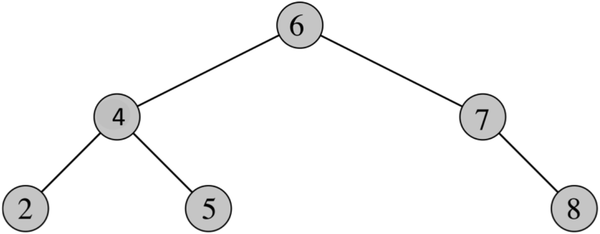

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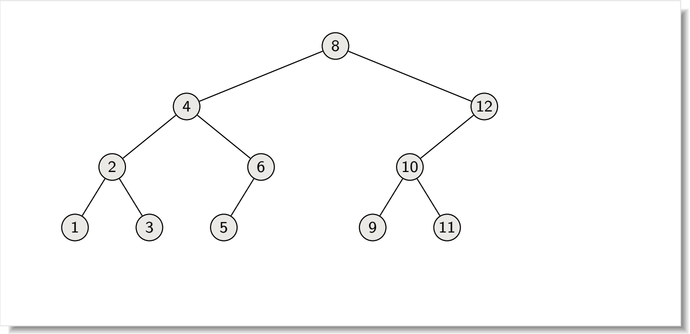
PRINTING A BINARY SEARCH TREE

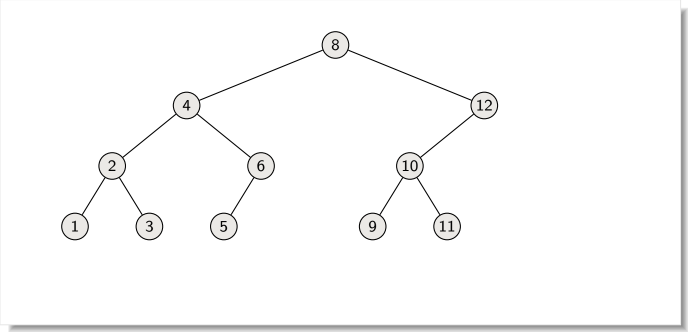
(Inorder, Preorder, Postorder)

Printing Inorder (Idea)



Printing Inorder (Idea)

- Print left subtree recursively
- Print root
- Print right subtree recursively



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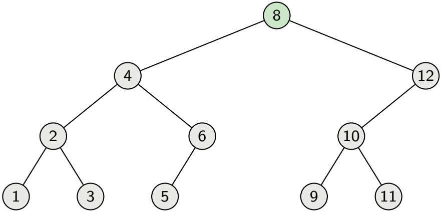
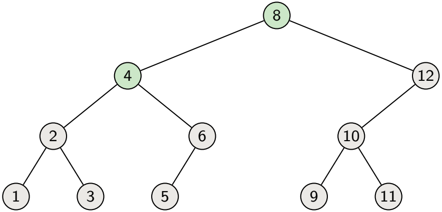


Output:

Printing Inorder (Idea)

- Print left subtree recursively
- Print root
- Print right subtree recursively



Output:

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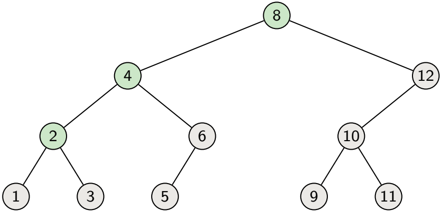

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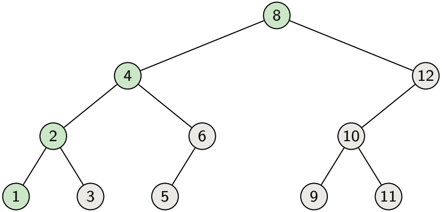

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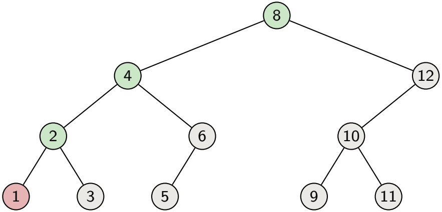

Output: 1,

Printing Inorder (Idea)

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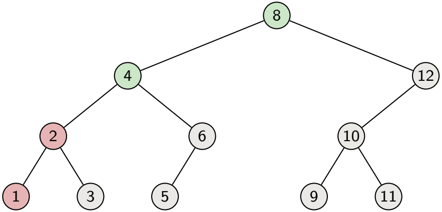
- Print right subtree recursively



Output: 1,2,

Printing Inorder (Idea)

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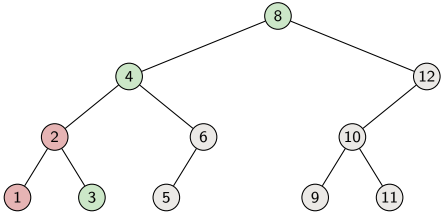

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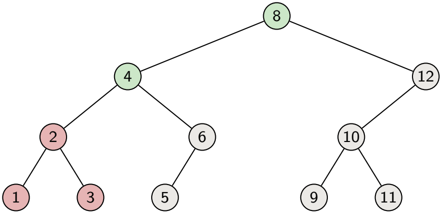

Output: 1,2,3,

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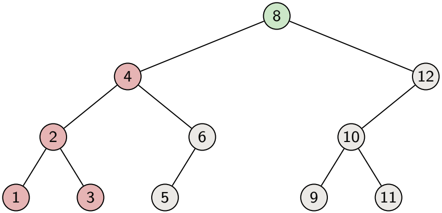
- Print root
- Print right subtree recursively



Output: 1,2,3,4,

Printing Inorder (Idea)

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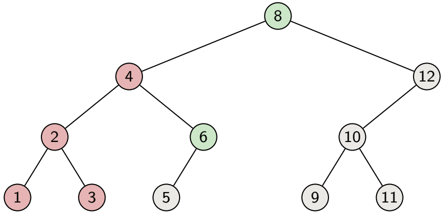
- Print right subtree recursively



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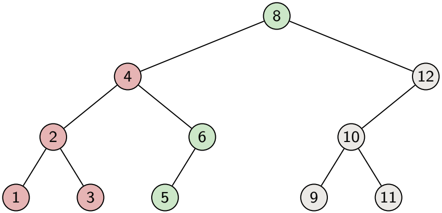

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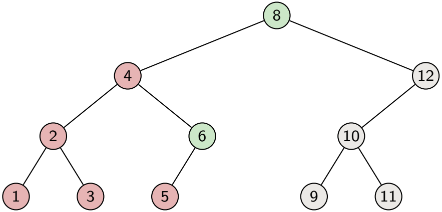

Output: 1,2,3,4,5,

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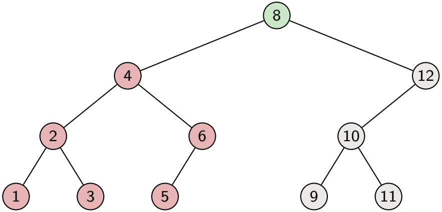

Output: 1,2,3,4,5,6,

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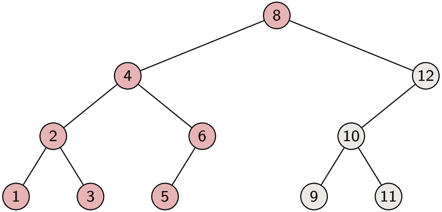

Output: 1,2,3,4,5,6,8,

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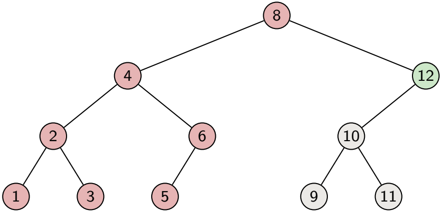

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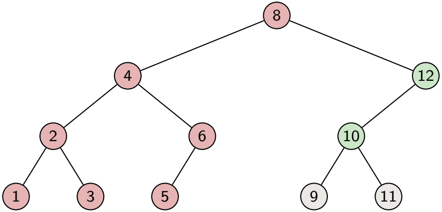

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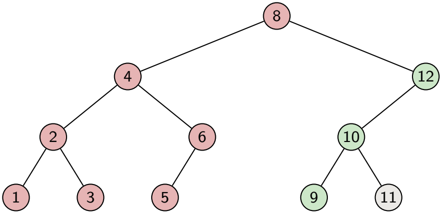

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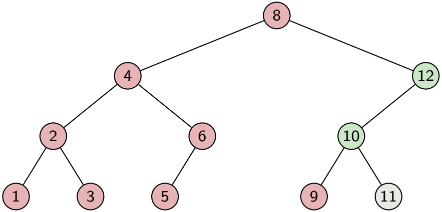

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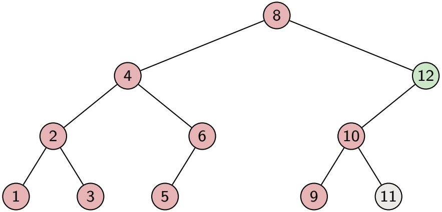

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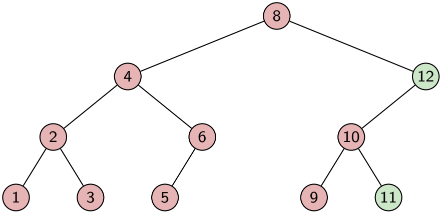

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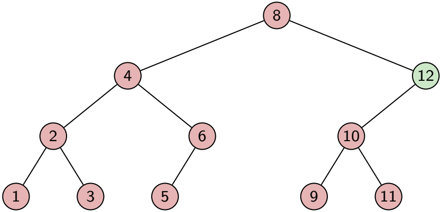

Output: 1,2,3,4,5,6,8,9,10,11,

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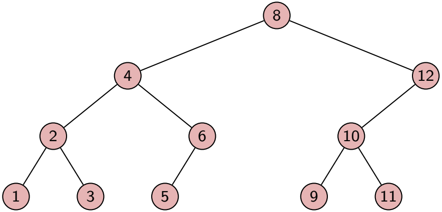
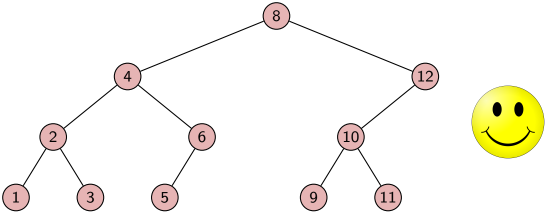
- Print right subtree recursively



Output: 1,2,3,4,5,6,8,9,10,11,12

Printing Inorder (Idea)

- Print left subtree recursively
- Print root
- Print right subtree recursively



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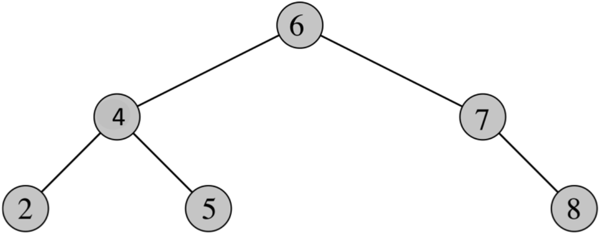
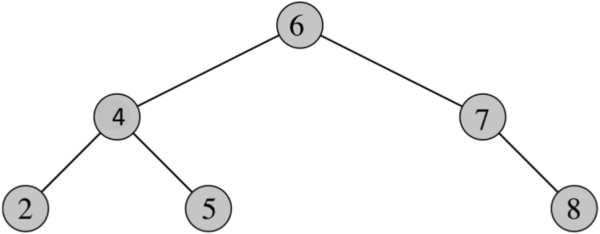
Inorder tree walk




```
INORDER-TREE-WALK(x)
  if x ≠ NIL
      INORDER-TREE-WALK(x.left)
      print key[x]
      INORDER-TREE-WALK(x.right)
```

Inorder tree walk



What is the running time?

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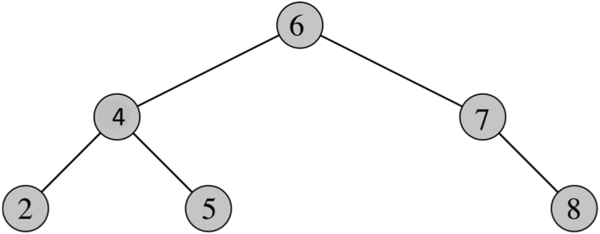

What is the running time? $\Theta(n)$

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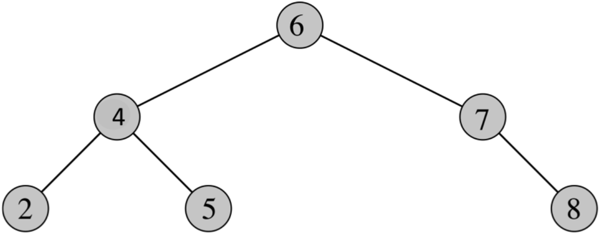
Printing Preorder and Postorder



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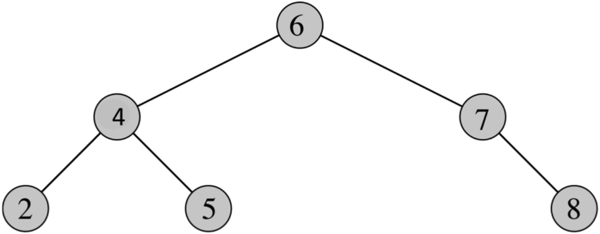

PREORDER-TREE-WALK(x)

1. **if** $x \neq NIL$
2. print $key[x]$
3. PREORDER-TREE-WALK($x.left$)
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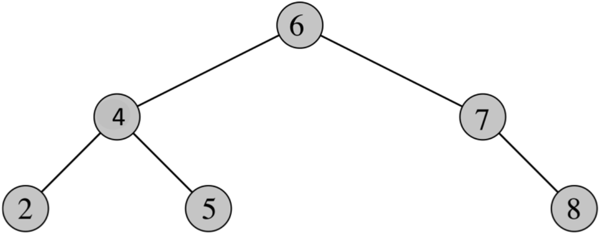

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POSTORDER-TREE-WALK(x)

1. **if** $x \neq NIL$
2. POSTORDER-TREE-WALK($x.left$)
3. POSTORDER-TREE-WALK($x.right$)
4. print $key[x]$

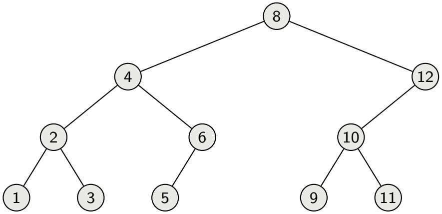
MODIFYING A BINARY SEARCH TREE

(Insertion and Deletion)

Idea of inserting z

- Search for $z.key$
- When arrived at *nil* insert z at that position

Ex: insert z with key 7



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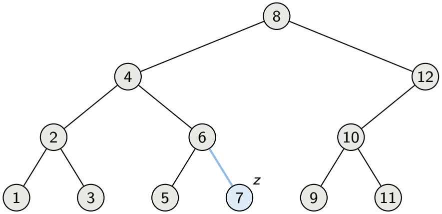

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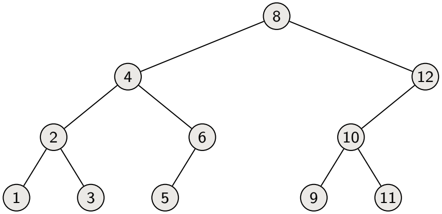

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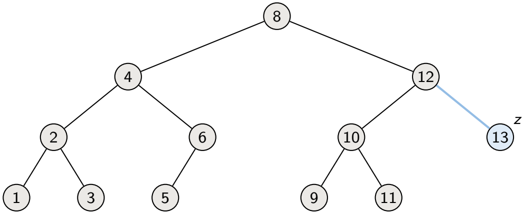

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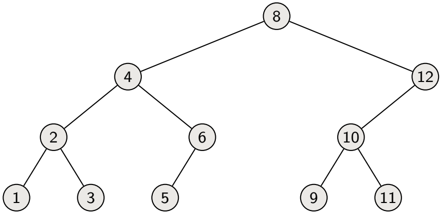

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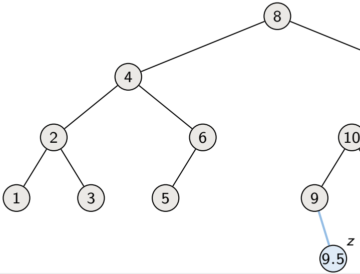

Insertion

"search" phase

"insert" phase

TREE-INSERT(T, z)

```
y = NIL
x = T.root
while x ≠ NIL
      y = x
      if z.key < x.key
            x = x.left
      else x = x.right
z.p = y
if y == NIL
      T.root = z          // tree T was empty
elseif z.key < y.key
      y.left = z
else y.right = z
```

Insertion

"search" phase

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```

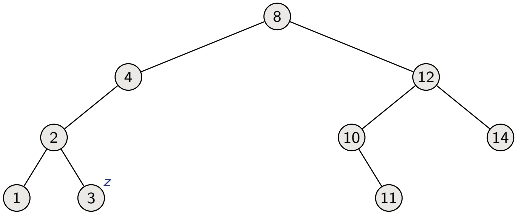
What is the running time? $O(h)$

Idea of deletion

Conceptually 3 cases:

- If z has no children, remove it

Ex: Delete z



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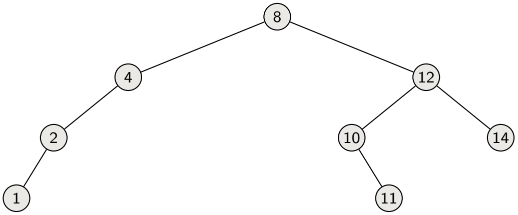

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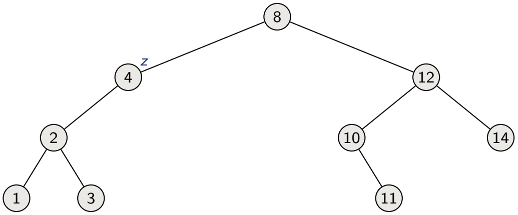

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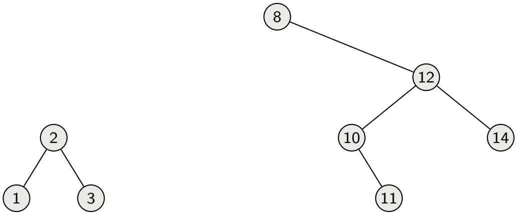

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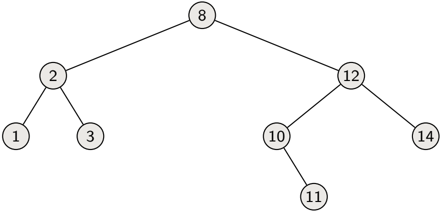

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Conceptually 3 cases:

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- If z has two children, then find its successor y and replace z by y

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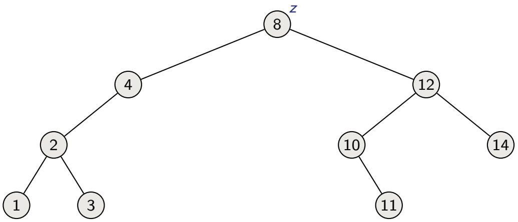

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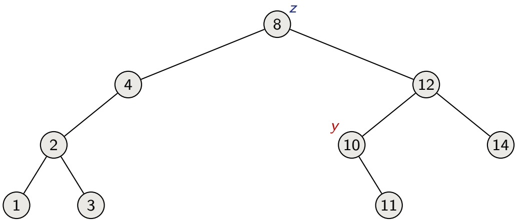

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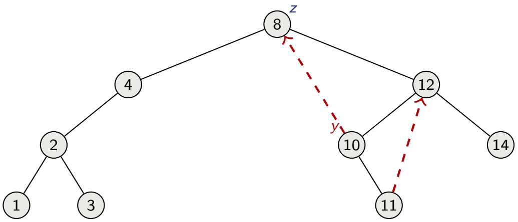

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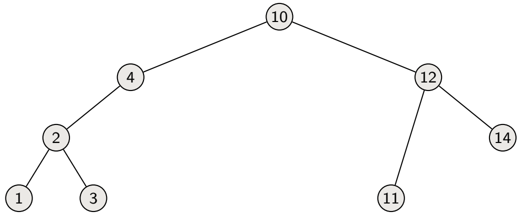
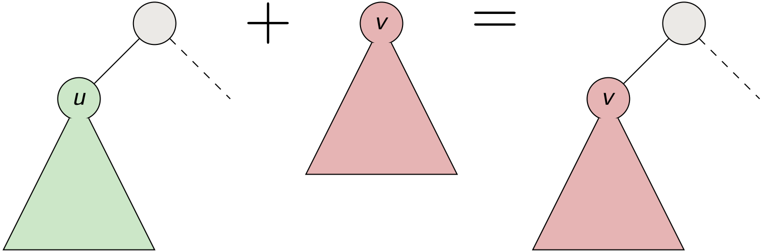


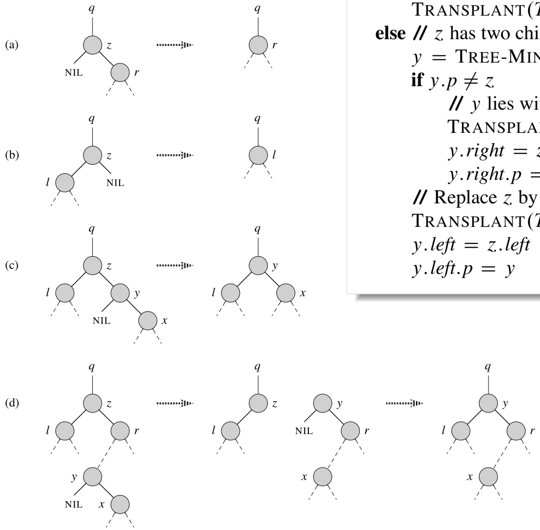
Deletion Implementation: Transplant

TRANSPLANT(T, u, v)
if $u.p$ == NIL
    $T.root = v$
elseif $u == u.p.left$
    $u.p.left = v$
else $u.p.right = v$
if $v \neq$ NIL
    $v.p = u.p$

TRANSPLANT(T, u, v) replaces subtree rooted at u with that rooted at v



Deletion Procedure




```
TREE-DELETE(T, z)
  if z.left == NIL
      TRANSPLANT(T, z, z.right)          // z has no left child
  elseif z.right == NIL
      TRANSPLANT(T, z, z.left)           // z has just a left child
  else // z has two children.
      y = TREE-MINIMUM(z.right)          // y is z's successor
      if y.p ≠ z
          // y lies within z's right subtree but is not the root of this
          TRANSPLANT(T, y, y.right)
          y.right = z.right
          y.right.p = y
      // Replace z by y.
      TRANSPLANT(T, z, y)
      y.left = z.left
      y.left.p = y
```

Summary of Binary Search Trees

Query operations: Search, Max, Min, Predecessor, Successor: **O(h)** time

Modifying operations: Insertion, Deletion: **O(h)** time

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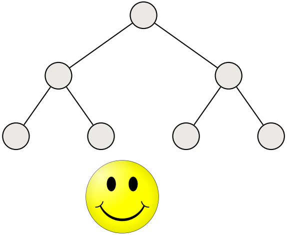
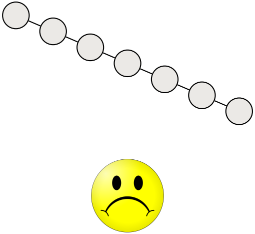


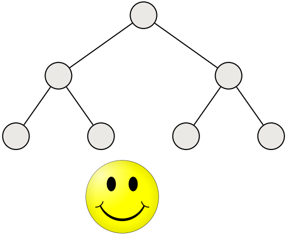


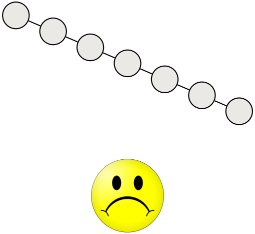
Summary of Binary Search Trees

Query operations: Search, Max, Min, Predecessor, Successor: **O(h)** time

Modifying operations: Insertion, Deletion: **O(h)** time

Exist efficient procedures to keep tree balanced (AVL trees, red-black trees, etc.)





Comparison of Data Structures

Stacks: Last-in-first-out, Insertion and deletion $O(1)$ time,
Array implementation: fixed capacity

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Binary Search Trees: No fixed capacity, supports most operations (insertion, deletion, search, max, min, ...) in time $O(\text{height of tree})$

DYNAMIC PROGRAMMING

(An algorithmic paradigm not a way of “programming”)

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Dynamic Programming (DP)

Main idea:

- Remember calculations already made
- Saves enormous amounts of computation

Allows to solve many optimization problems

- Always at least one question in google code jam needs DP

First application: Fibonacci numbers

Sequence of numbers defined 1000 years ago:

$$F_0 = 1$$
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$$F_n = F_{n-1} + F_{n-2}$$

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1, 1, 2, 3, 5, 8, 13, 21, ?

Calculating the *n*-th Fibonacci number

Calculating the n-th Fibonacci number

First idea:

FIB(n)

1. **if** $n = 0$ or $n = 1$
2. **return** 1
3. **else**
4. **return** FIB($n - 1$) + FIB($n - 2$)

Calculating the n-th Fibonacci number

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Calculating the n-th Fibonacci number

First idea:

```
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    return FIB(n − 1) + FIB(n − 2)
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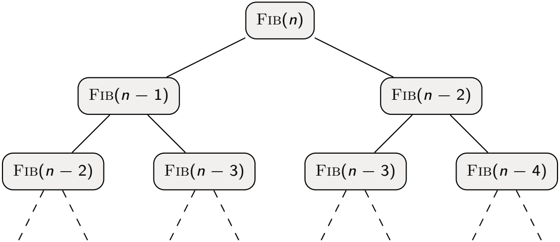
What is the problem?



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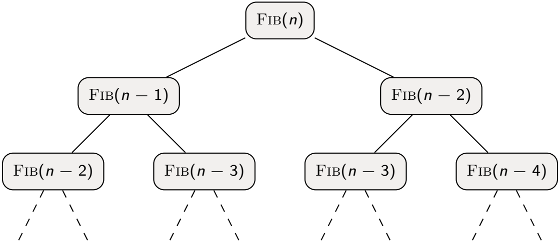
What is the problem? Same calculations again and again $\Rightarrow$ exponential time!



The solution

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Two different ways:

1. Top-down with memoization
    - Solve recursively but store each result in a table
    - Memoizing is remembering what we have computed previously

The solution

Remember what we have done

Two different ways:

1. Top-down with memoization
   - Solve recursively but store each result in a table
   - Memoizing is remembering what we have computed previously
2. Bottom-up
   - Sort the subproblems and solve the smaller ones first
   - That way, when solving a subproblem, have already solved the smaller subproblems we need

Top-down with memoization: Fibonacci numbers

MEMOIZED-FIB(n)

1. Let $r = [0 \ldots n]$ be a new array
2. **for** $i = 0$ **to** n
3. $\quad r[i] \leftarrow -\infty$
4. **return** MEMOIZED-FIB-AUX(n, r)

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MEMOIZED-FIB-AUX(n, r)

1. **if** $r[n] \geq 0$
2. $\quad$ **return** $r[n]$
3. **if** $n = 0$ or $n = 1$
4. $\quad ans \leftarrow 1$
5. **else**
6. $\quad ans \leftarrow$ MEMOIZED-FIB-AUX($n-1, r$)+ MEMOIZED-FIB-AUX($n-2, r$)
7. $r[n] \leftarrow ans$
8. **return** $r[n]$

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Top-down with memoization: Fibonacci numbers

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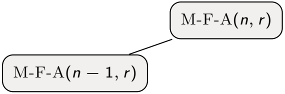

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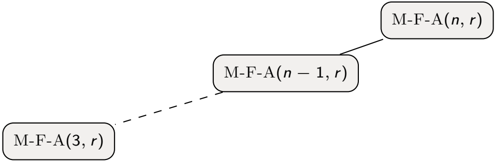

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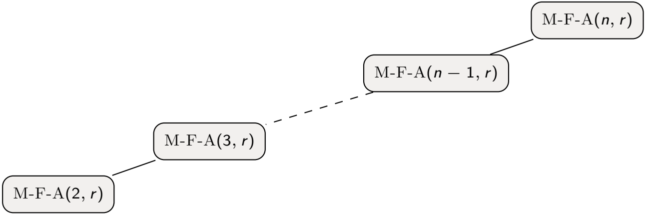

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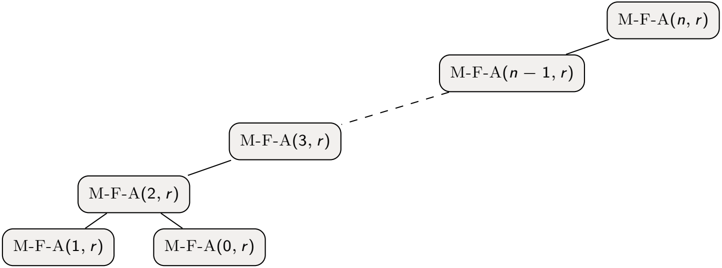

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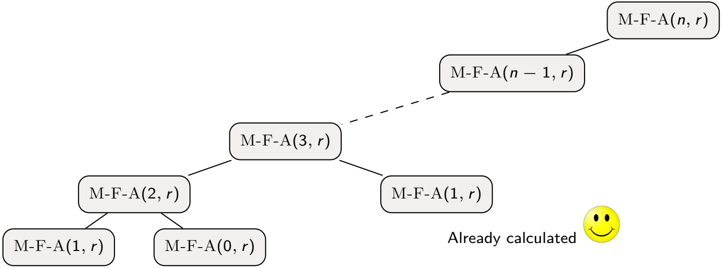

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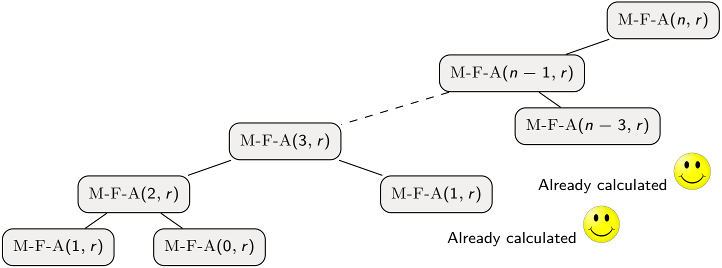

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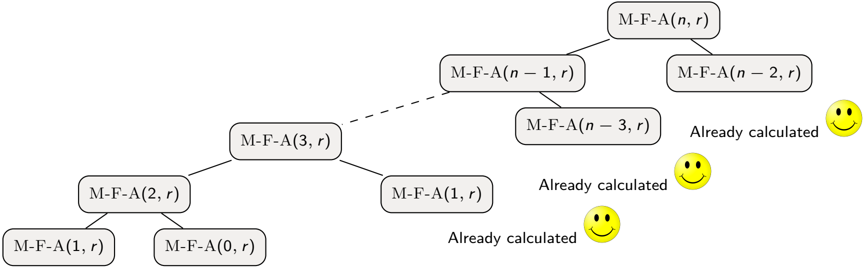

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- Total time is thus $\Theta(n)$

Bottom-up: Fibonacci numbers

```
BOTTOM-UP-FIB(n)

Let r = [0 . . . n] be a new array
r[0] ← 1
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for i = 2 to n
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Example $n = 8$:

$r =$

1							

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1	1	2	3	5			

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Time? $\Theta(n)$

Summary

- We had a recursive formulation of our problem

$$F_0 = 1$$
$$F_1 = 1$$
$$F_n = F_{n-1} + F_{n-2}$$

- Introduced memory (array r)
- Filled in table"top-down with memoization" or with "bottom-up"

Key elements in designing a DP-algorithm

Optimal substructure

- Show that a solution to a problem consists of making a choice, which leaves one or several subproblems to solve

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Overlapping subproblems

- A naive recursive algorithm may revisit the same (sub)problem over and over.
- Top-down with memoization

  Solve recursively but store each result in a table
- Bottom-up

  Sort the subproblems and solve the smaller ones first; that way, when solving a subproblem, have already solved the smaller subproblems we need

ROD CUTTING

Rod cutting

Instance:

- A length n of a metal rod.
- A table of prices p_i for rods of lengths $i = 1, \ldots, n$.

length i	1	2	3	4	5	6	7	8	9	10
price p_i	1	5	8	9	10	17	17	20	24	30

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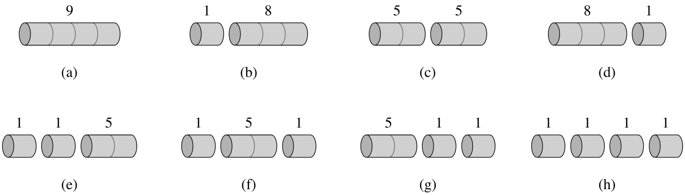

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Theorem

If:

- *the leftmost cut in an optimal solution is after i units.*
- *an optimal way to cut a solution of size $n - i$ is into rods of sizes: $s_1, s_2, \ldots, s_k$.*

Then, an optimal way to cut our rod is into rods of sizes: $i, s_1, s_2, \ldots, s_k$.

Proof of Structural Theorem

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Feasibility: Since $s_1, s_2, \ldots, s_k$ is a feasible solution for an instance of size $n - i$:

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Hence, $i + \sum_{j=1}^{k} s_j = n$.

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Hence, $p_i + \sum_{j=1}^{k} p_{s_j} \geq p_i + \sum_{j=1}^{\ell} p_{o_j}$.

First Algorithm

If we let $r(n)$ be the optimal revenue from a rod of length n, then, by the structural theorem, we can express $r(n)$ recursively as follows

$$r(n) = \begin{cases} 0 & \text{if } n = 0 \ , \\ \max_{1 \leq i \leq n} \{p_i + r(n-i)\} & \text{otherwise if } n \geq 1 \ . \end{cases}$$

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```
CUT-ROD(p, n)
  if n == 0
      return 0
  q = −∞
  for i = 1 to n
      q = max(q, p[i] + CUT-ROD(p, n − i))
  return q
```

Problem

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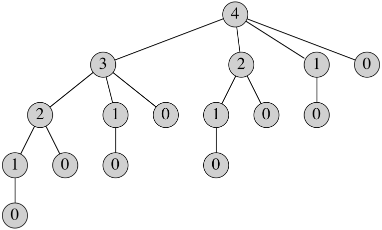

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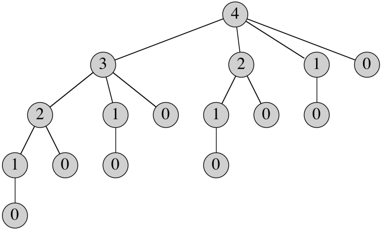

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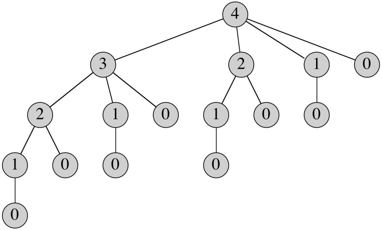

- The procedure repeatedly calculates the same profits.
- Dynamic programming can save the extra calculations.

Top-Down Dynamic Programming

General Approach

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Pseudocode

```
MEMOIZED-CUT-ROD(p, n)
  let r[0..n] be a new array
  for i = 0 to n
      r[i] = −∞
  return MEMOIZED-CUT-ROD-AUX(p, n, r)
```

Top-Down Dynamic Programming

General Approach

- Keep the recursive structure of the pseudocode.
- Memoize (store) the result of every recursive call.
- At each recursive call, try to avoid work using memoized results.

Pseudocode

```
MEMOIZED-CUT-ROD-AUX(p, n, r)
  if r[n] ≥ 0
      return r[n]
  if n == 0
      q = 0
  else q = −∞
      for i = 1 to n
          q = max(q, p[i] + MEMOIZED-CUT-ROD-AUX(p, n − i, r))
  r[n] = q
  return q
```

```
MEMOIZED-CUT-ROD(p, n)
  let r[0..n] be a new array
  for i = 0 to n
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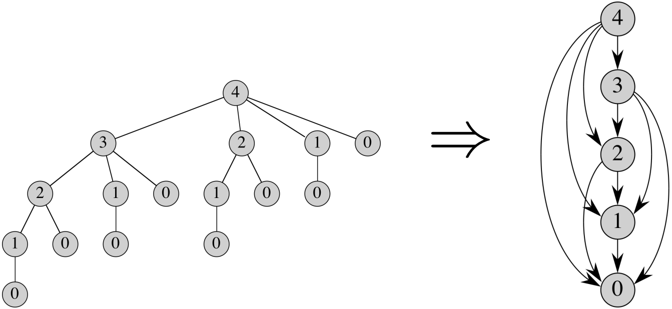

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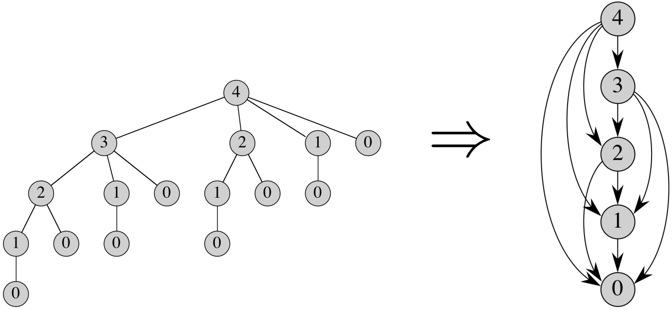

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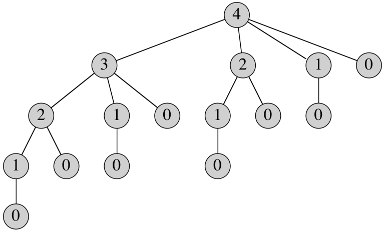
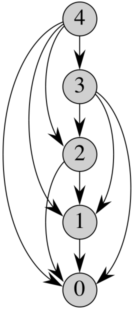


$\Rightarrow$

Subproblem Graph



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- Processing each sub-problem takes linear time in the number of sub-problems it evokes.

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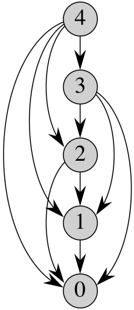

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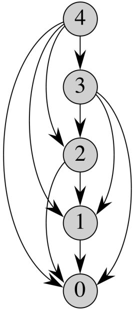

Time Complexity
$O(n^2)$

Bottom-Up Dynamic Programming

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Pseudocode

```
BOTTOM-UP-CUT-ROD(p, n)
  let r[0 . . n] be a new array
  r[0] = 0
  for j = 1 to n
      q = −∞
      for i = 1 to j
          q = max(q, p[i] + r[j − i])
      r[j] = q
  return r[n]
```

Bottom-Up Dynamic Programming

General Approach

- Sort the sub-problems by size.
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- When reaching a sub-problem, the smaller ones are already solved.

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- The above algorithms only return the optimal profit.
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Approach

- Each cell of the memoization table corresponds to a decision: the location of the left most cut.
- Store the decision corresponding to every cell in a separate table.

Reconstructing an Optimal Solution (cont.)

```
EXTENDED-BOTTOM-UP-CUT-ROD(p, n)
  let r[0..n] and s[0..n] be new arrays
  r[0] = 0
  for j = 1 to n
      q = −∞
      for i = 1 to j
          if q < p[i] + r[j − i]
              q = p[i] + r[j − i]
              s[j] = i
      r[j] = q
  return r and s
```

Reconstructing an Optimal Solution (cont.)

```
EXTENDED-BOTTOM-UP-CUT-ROD(p, n)
  let r[0..n] and s[0..n] be new arrays
  r[0] = 0
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          if q < p[i] + r[j − i]
              q = p[i] + r[j − i]
              s[j] = i
      r[j] = q
  return r and s
```

Output

i	0	1	2	3	4	5	6	7	8
r[i]	0	1	5	8	10	13	17	18	22
s[i]	0	1	2	3	2	2	6	1	2

Summary

- We had a recursive formulation for the optimal value for our problem

$$r(n) = \begin{cases} 0 & \text{if } n = 0 \ , \\ \max_{1 \leq i \leq n} \{p_i + r(n-i)\} & \text{otherwise if } n \geq 1 \ . \end{cases}$$

- Speed up the calculations by filling in a table either "top-down with memoization" or with "bottom-up".
- Recovered an optimal solution using an additional table.

Problem Solving: the Change-Making Problem

- How can a given amount of money be made with the least number of coins of given denominations?

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Formally:

Input: n distinct coin denominators (integers) $0 < w_1 < w_2 < \ldots < w_n$ and an amount W (the change) which is also a positive integer.

Output: The minimum number of coins needed in order to make the change:

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Example: On input $w_1 = 1, w_2 = 2, w_3 = 5$ and $W = 8$, the output should be 3 since the best way of giving 8 is $x_1 = x_2 = x_3 = 1$.

Summary

- Identify choices and optimal substructure
- Write optimal solution recursively as a function of smaller subproblems
- Use top-down with memoization or bottom-up to solve the recursion efficiently (without repeatedly solving the same subproblems)