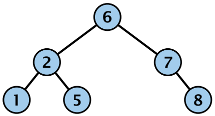
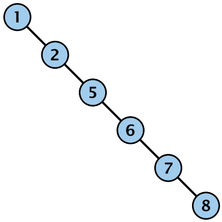
7.1 Binary Search Trees

An (internal) binary search tree stores the elements in a binary tree. Each tree-node corresponds to an element. All elements in the left sub-tree of a node v have a smaller key-value than $\mathrm{key}[v]$ and elements in the right sub-tree have a larger-key value. We assume that all key-values are different.

(External Search Trees store objects only at leaf-vertices)

Examples:



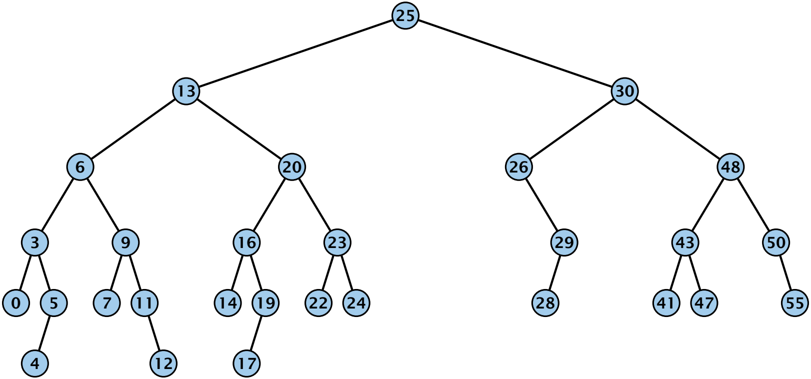


7.1 Binary Search Trees

We consider the following operations on binary search trees. Note that this is a super-set of the dictionary-operations.

- $T.\,\mathrm{insert}(x)$
- $T.\,\mathrm{delete}(x)$
- $T.\,\mathrm{search}(k)$
- $T.\,\mathrm{successor}(x)$
- $T.\,\mathrm{predecessor}(x)$
- $T.\,\mathrm{minimum}()$
- $T.\,\mathrm{maximum}()$

Binary Search Trees: Searching

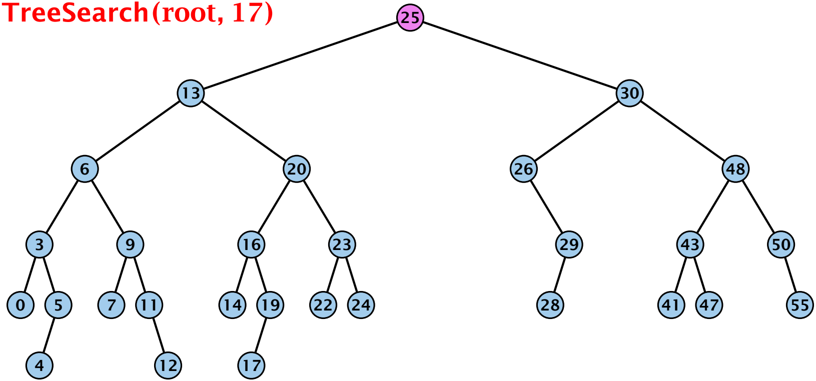


Algorithm 1 TreeSearch(x, k)

1: **if** x = null **or** k = key$[x]$ **return** x
2: **if** $k <$ key$[x]$ **return** TreeSearch(left$[x], k$)
3: **else return** TreeSearch(right$[x], k$)

Binary Search Trees: Searching

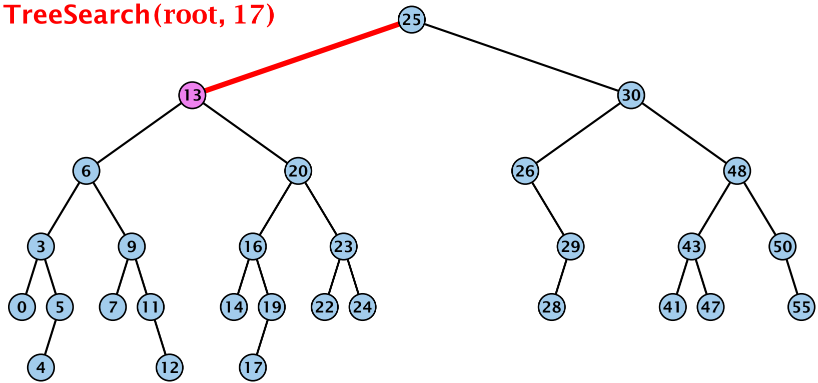
TreeSearch(root, 17)



Algorithm 1 TreeSearch(x, k)

if $x = \text{null}$ **or** $k = \text{key}[x]$ **return** x
if $k < \text{key}[x]$ **return** TreeSearch$(\text{left}[x], k)$
else return TreeSearch$(\text{right}[x], k)$

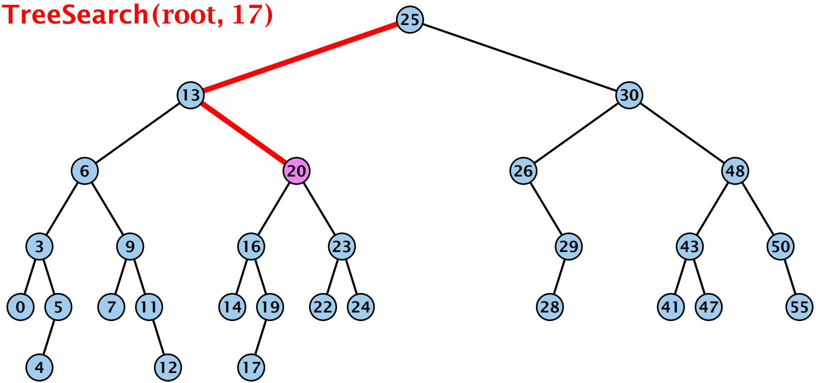
Binary Search Trees: Searching



Algorithm 1 TreeSearch(x, k)

1: **if** x = null **or** $k = \text{key}[x]$ **return** x
2: **if** $k < \text{key}[x]$ **return** TreeSearch$(\text{left}[x], k)$
3: **else return** TreeSearch$(\text{right}[x], k)$

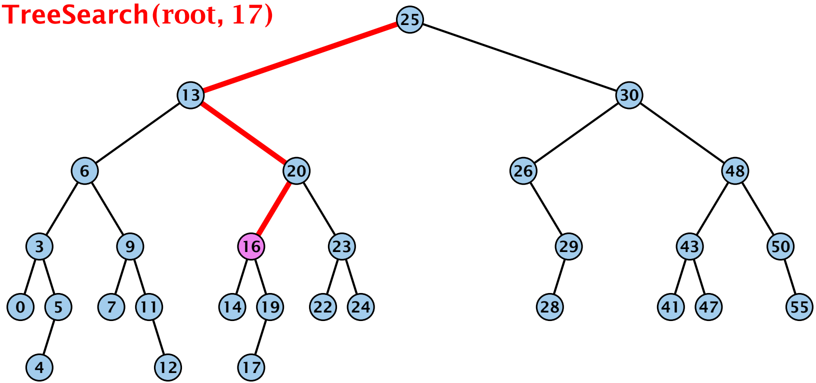
Binary Search Trees: Searching



Algorithm 1 TreeSearch(x, k)

1: **if** x = null **or** $k = \text{key}[x]$ **return** x
2: **if** $k < \text{key}[x]$ **return** TreeSearch$(\text{left}[x], k)$
3: **else return** TreeSearch$(\text{right}[x], k)$

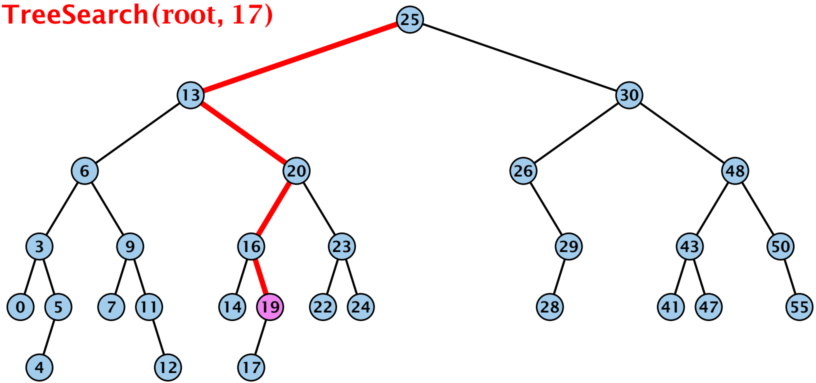
Binary Search Trees: Searching



Algorithm 1 TreeSearch(x, k)

1: **if** x = null **or** k = key[x] **return** x
2: **if** $k <$ key[x] **return** TreeSearch(left[x], k)
3: **else return** TreeSearch(right[x], k)

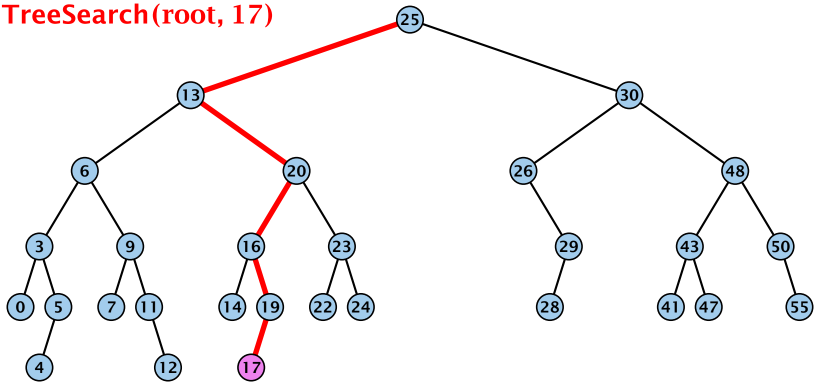
Binary Search Trees: Searching



Algorithm 1 TreeSearch(x, k)

1: **if** $x = \text{null}$ **or** $k = \text{key}[x]$ **return** x
2: **if** $k < \text{key}[x]$ **return** TreeSearch$(\text{left}[x], k)$
3: **else return** TreeSearch$(\text{right}[x], k)$

Binary Search Trees: Searching



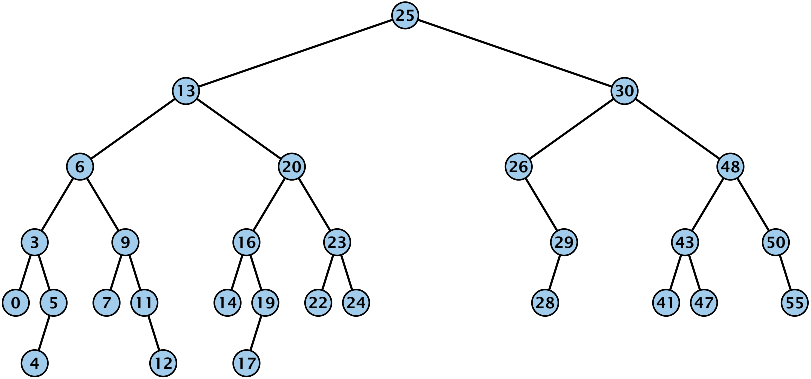
Algorithm 1 TreeSearch(x, k)

1: **if** $x = \text{null}$ **or** $k = \text{key}[x]$ **return** x

2: **if** $k < \text{key}[x]$ **return** TreeSearch$(\text{left}[x], k)$

3: **else return** TreeSearch$(\text{right}[x], k)$

Binary Search Trees: Searching



Algorithm 1 TreeSearch(x, k)

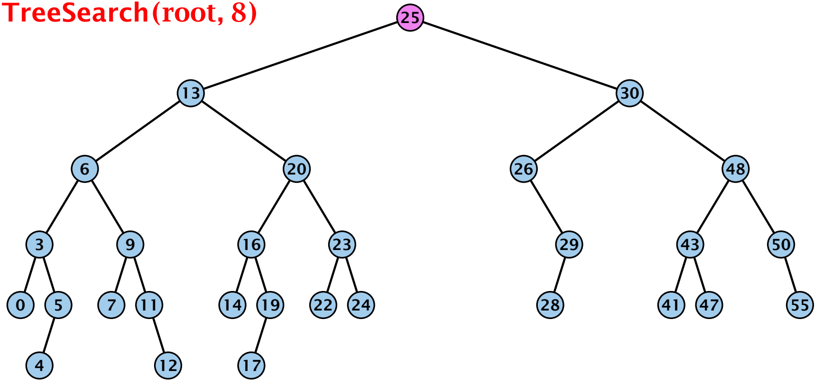
1: **if** $x = \text{null}$ **or** $k = \text{key}[x]$ **return** x

2: **if** $k < \text{key}[x]$ **return** TreeSearch$(\text{left}[x], k)$

3: **else return** TreeSearch$(\text{right}[x], k)$

Binary Search Trees: Searching

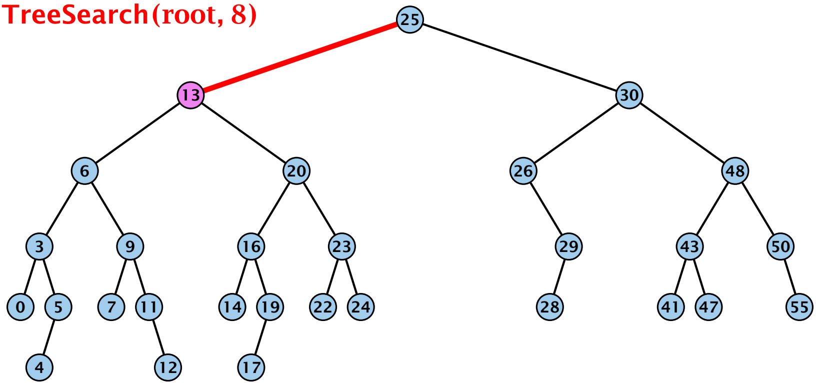
TreeSearch(root, 8)



Algorithm 1 TreeSearch(x, k)

1: **if** $x = \text{null}$ **or** $k = \text{key}[x]$ **return** x
2: **if** $k < \text{key}[x]$ **return** TreeSearch$(\text{left}[x], k)$
3: **else return** TreeSearch$(\text{right}[x], k)$

Binary Search Trees: Searching



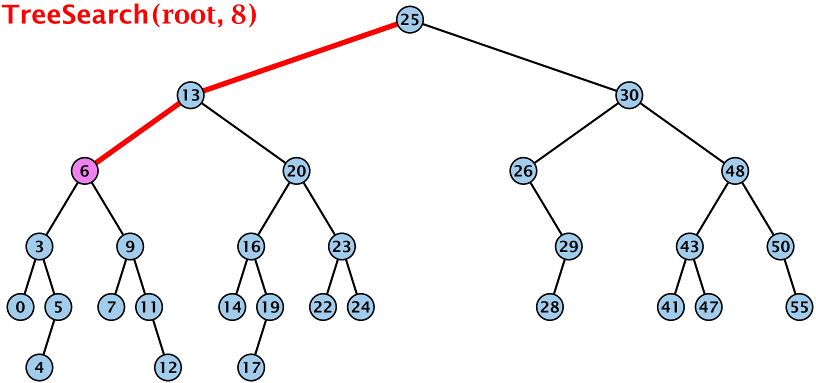
Algorithm 1 TreeSearch(x, k)

1: **if** x = null **or** k = key[x] **return** x

2: **if** $k <$ key[x] **return** TreeSearch(left[x], k)

3: **else return** TreeSearch(right[x], k)

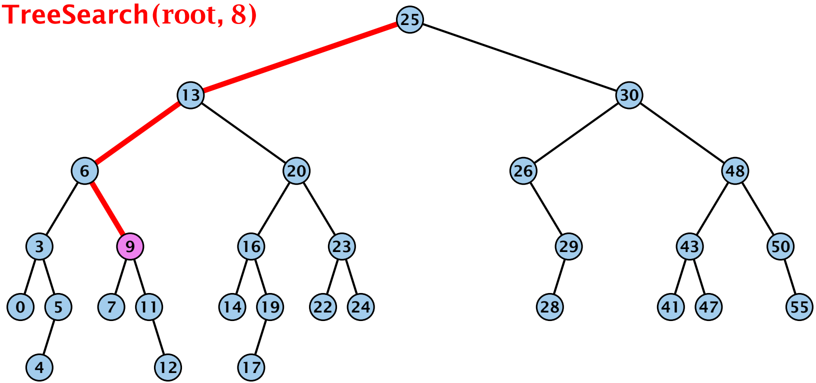
Binary Search Trees: Searching



Algorithm 1 TreeSearch(x, k)

1: **if** x = null **or** $k = \text{key}[x]$ **return** x
2: **if** $k < \text{key}[x]$ **return** TreeSearch(left[x], k)
3: **else return** TreeSearch(right[x], k)

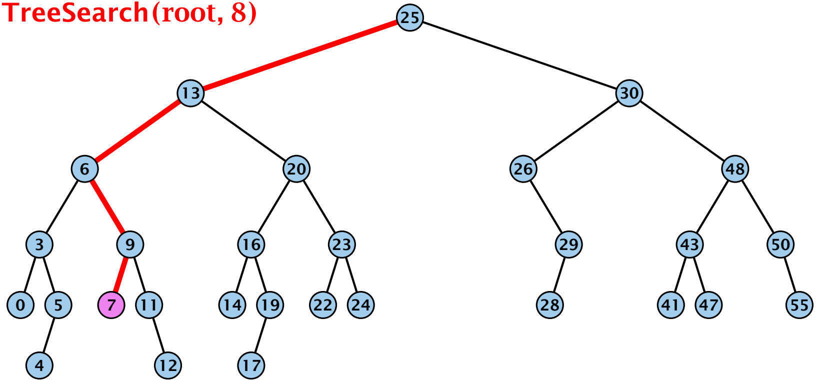
Binary Search Trees: Searching



Algorithm 1 TreeSearch(x, k)

1: **if** x = null **or** $k = \text{key}[x]$ **return** x
2: **if** $k < \text{key}[x]$ **return** TreeSearch$(\text{left}[x], k)$
3: **else return** TreeSearch$(\text{right}[x], k)$

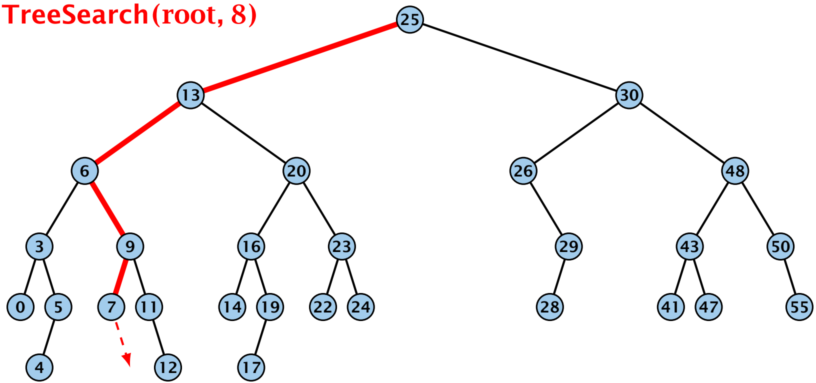
Binary Search Trees: Searching



Algorithm 1 TreeSearch(x, k)

if $x = \text{null}$ **or** $k = \text{key}[x]$ **return** x
if $k < \text{key}[x]$ **return** TreeSearch$(\text{left}[x], k)$
else return TreeSearch$(\text{right}[x], k)$

Binary Search Trees: Searching



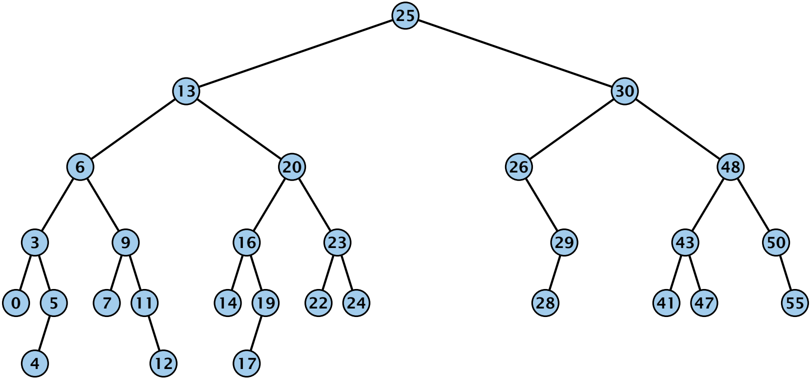
Algorithm 1 TreeSearch(x, k)

1: **if** $x = \text{null}$ **or** $k = \text{key}[x]$ **return** x

2: **if** $k < \text{key}[x]$ **return** TreeSearch$(\text{left}[x], k)$

3: **else return** TreeSearch$(\text{right}[x], k)$

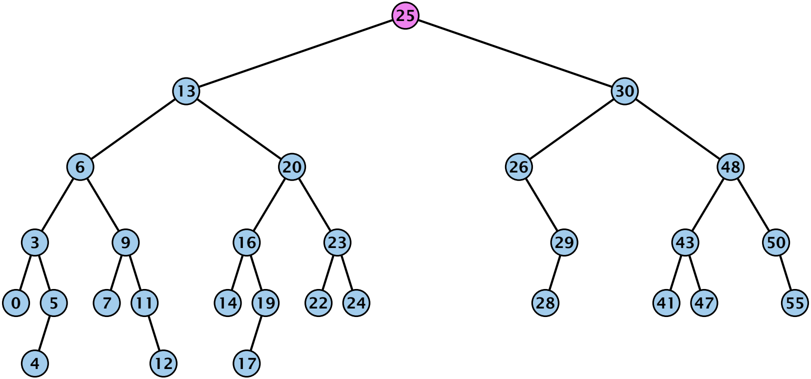
Binary Search Trees: Minimum



Algorithm 2 TreeMin(x)

1: **if** x = null **or** left$[x]$ = null **return** x
2: **return** TreeMin(left$[x]$)

Binary Search Trees: Minimum

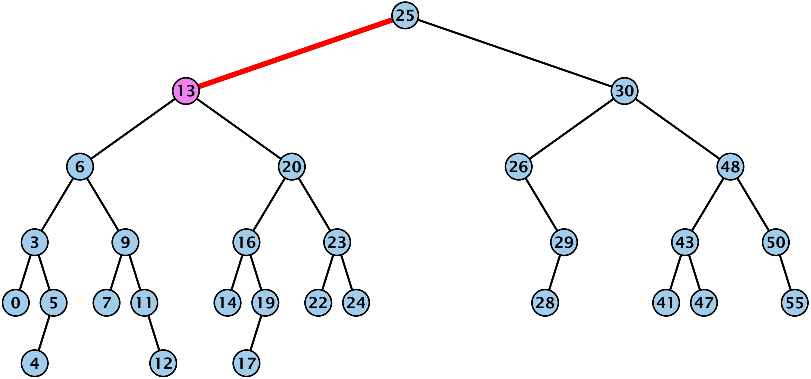


Algorithm 2 TreeMin(x)

1: **if** $x = \text{null}$ **or** $\text{left}[x] = \text{null}$ **return** x

2: **return** TreeMin($\text{left}[x]$)

Binary Search Trees: Minimum

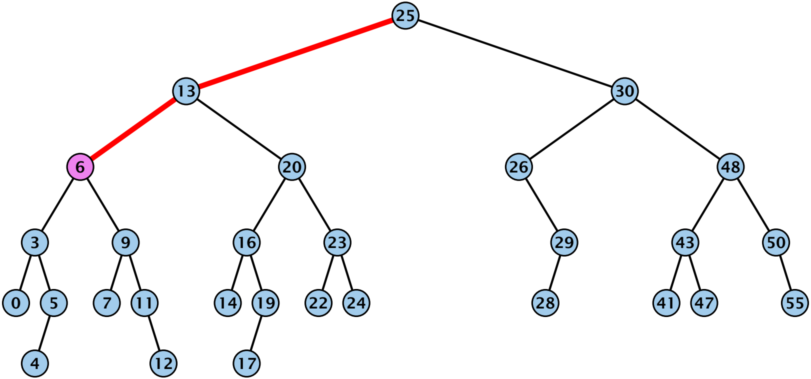


Algorithm 2 TreeMin(x)

1: **if** $x = \text{null}$ **or** $\text{left}[x] = \text{null}$ **return** x

2: **return** TreeMin($\text{left}[x]$)

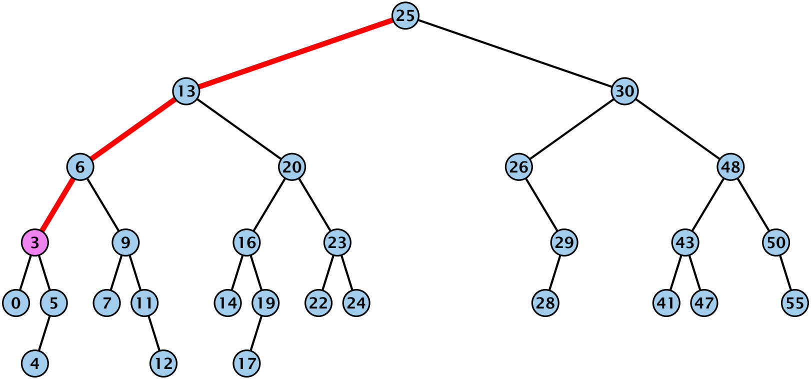
Binary Search Trees: Minimum



Algorithm 2 TreeMin(x)

1: **if** x = null **or** left[x] = null **return** x
2: **return** TreeMin(left[x])

Binary Search Trees: Minimum

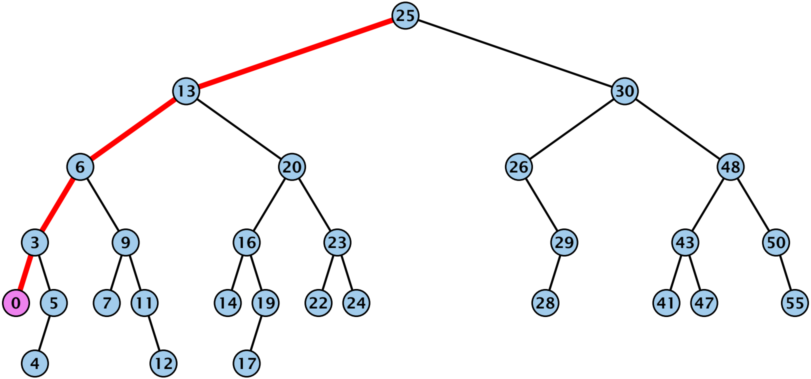


Algorithm 2 TreeMin(x)

1: **if** $x = \text{null}$ **or** $\text{left}[x] = \text{null}$ **return** x

2: **return** TreeMin($\text{left}[x]$)

Binary Search Trees: Minimum

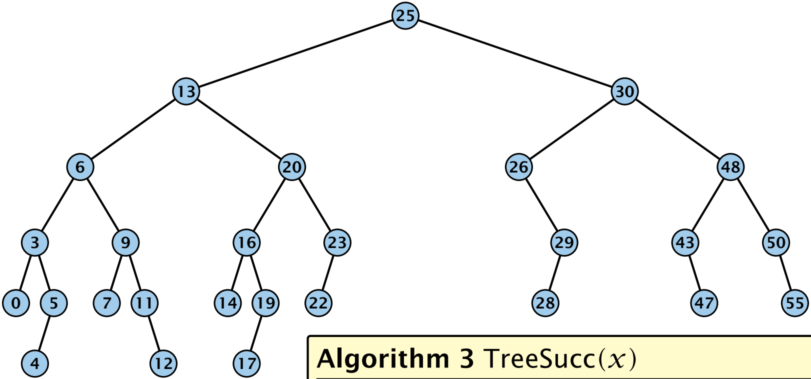


Algorithm 2 TreeMin(x)

1: **if** $x = \text{null}$ **or** $\text{left}[x] = \text{null}$ **return** x

2: **return** TreeMin$(\text{left}[x])$

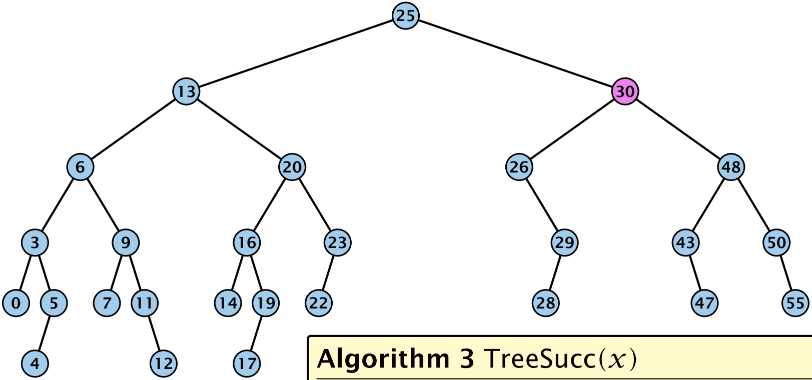
Binary Search Trees: Successor



Algorithm 3 TreeSucc(x)

if right[x] $\neq$ null **return** TreeMin(right[x])
$y \leftarrow$ parent[x]
while $y \neq$ null **and** $x =$ right[y] **do**
    $x \leftarrow y; y \leftarrow$ parent[x]
return y;

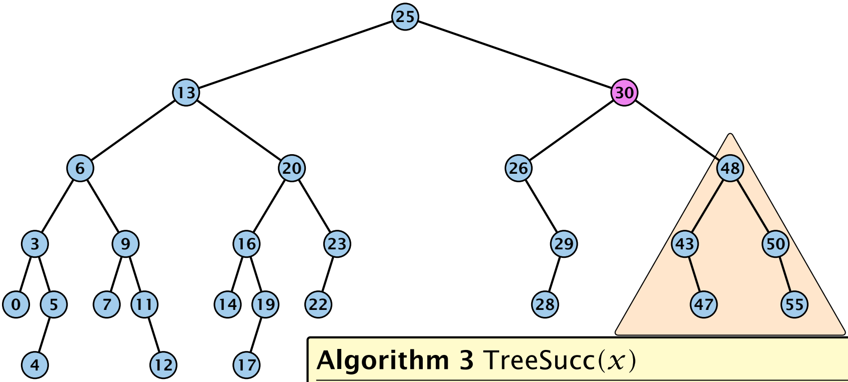
Binary Search Trees: Successor



Algorithm 3 TreeSucc(x)

1: **if** right[x] $\neq$ null **return** TreeMin(right[x])
2: $y \leftarrow$ parent[x]
3: **while** $y \neq$ null **and** $x =$ right[y] **do**
4: $\quad x \leftarrow y; y \leftarrow$ parent[x]
5: **return** y;

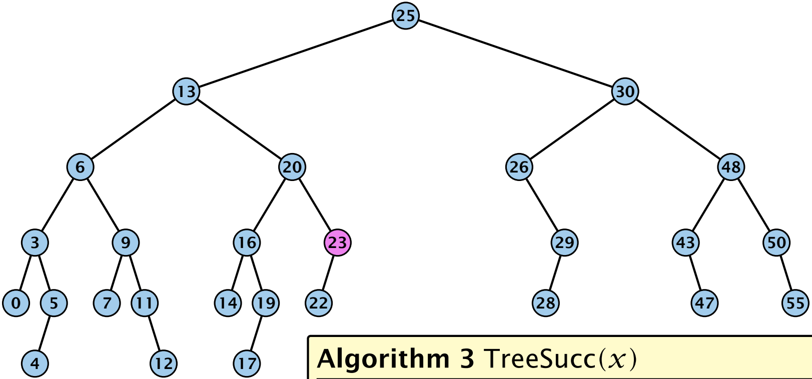
Binary Search Trees: Successor



Algorithm 3 TreeSucc(x)

if right[x] $\neq$ null **return** TreeMin(right[x])
$y \leftarrow$ parent[x]
while $y \neq$ null **and** $x =$ right[y] **do**
    $x \leftarrow y$; $y \leftarrow$ parent[x]
return y;

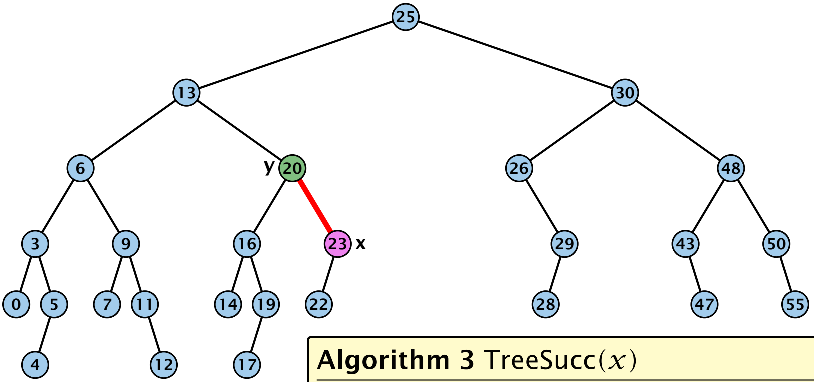
Binary Search Trees: Successor



Algorithm 3 TreeSucc(x)

1: **if** right$[x] \neq$ null **return** TreeMin(right$[x]$)
2: $y \leftarrow$ parent$[x]$
3: **while** $y \neq$ null **and** $x =$ right$[y]$ **do**
4: $\quad x \leftarrow y; y \leftarrow$ parent$[x]$
5: **return** y;

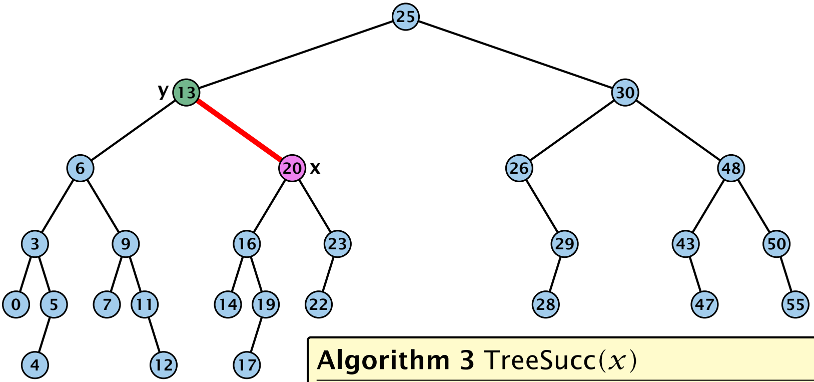
Binary Search Trees: Successor



Algorithm 3 TreeSucc(x)

if right[x] $\neq$ null **return** TreeMin(right[x])
$y \leftarrow$ parent[x]
while $y \neq$ null **and** $x =$ right[y] **do**
  $x \leftarrow y$; $y \leftarrow$ parent[x]
return y;

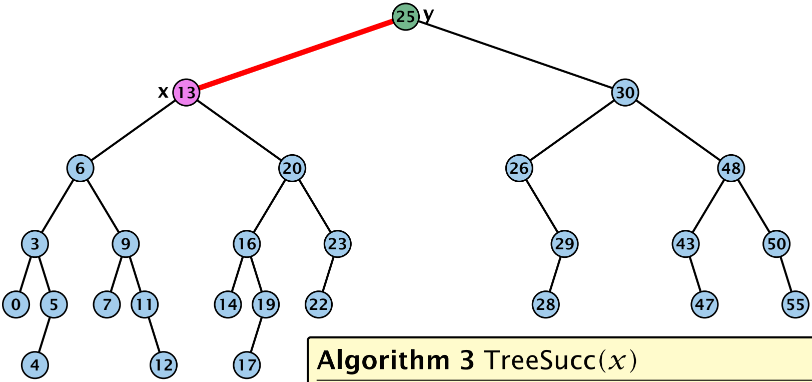
Binary Search Trees: Successor



Algorithm 3 TreeSucc(x)

1: **if** right[x] $\neq$ null **return** TreeMin(right[x])
2: $y \leftarrow$ parent[x]
3: **while** $y \neq$ null **and** $x =$ right[y] **do**
4: $\quad x \leftarrow y$; $y \leftarrow$ parent[x]
5: **return** y;

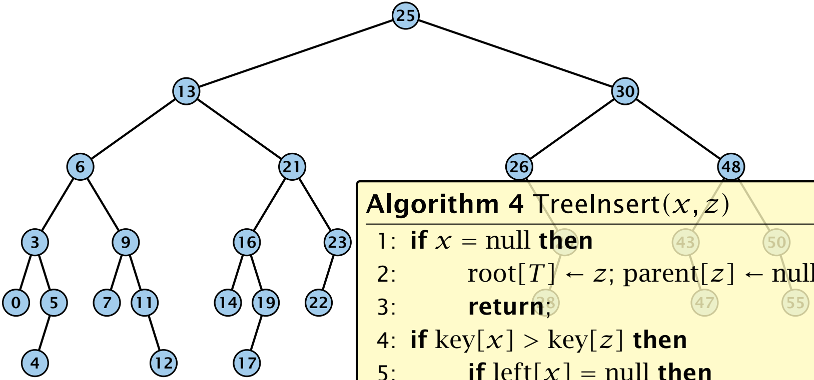
Binary Search Trees: Successor



Algorithm 3 TreeSucc(x)

if right[x] $\neq$ null **return** TreeMin(right[x])
$y \leftarrow$ parent[x]
while $y \neq$ null **and** $x =$ right[y] **do**
    $x \leftarrow y$; $y \leftarrow$ parent[x]
return y;

Binary Search Trees: Insert



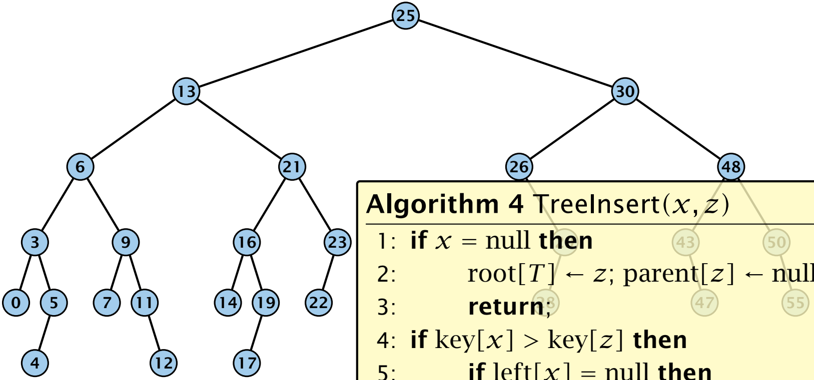
Algorithm 4 TreeInsert(x, z)

---

if x = null **then**
  root$[T] \leftarrow z$; parent$[z] \leftarrow$ null;
  return;
if key$[x] >$ key$[z]$ **then**
  if left$[x]$ = null **then**
    left$[x] \leftarrow z$; parent$[z] \leftarrow x$;
  else TreeInsert(left$[x], z$);
else
  if right$[x]$ = null **then**
    right$[x] \leftarrow z$; parent$[z] \leftarrow x$;
  else TreeInsert(right$[x], z$);

Binary Search Trees: Insert

Insert element **not** in the tree.

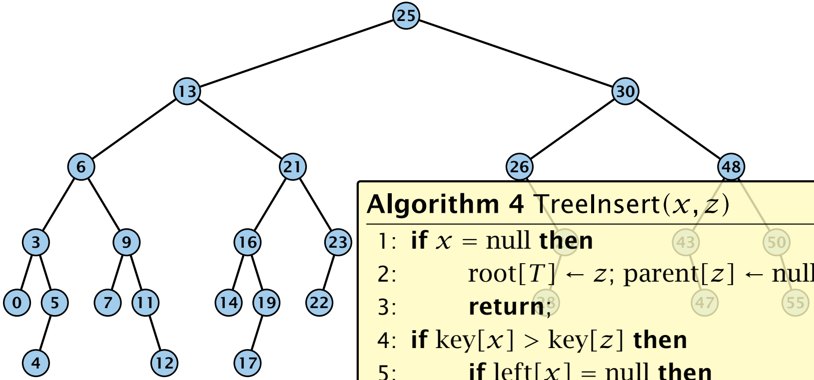


Algorithm 4 TreeInsert(x, z)

if x = null **then**
    root$[T] \leftarrow z$; parent$[z] \leftarrow$ null;
    return;
if key$[x] >$ key$[z]$ **then**
    if left$[x]$ = null **then**
        left$[x] \leftarrow z$; parent$[z] \leftarrow x$;
    else TreeInsert(left$[x], z$);
else
    if right$[x]$ = null **then**
        right$[x] \leftarrow z$; parent$[z] \leftarrow x$;
    else TreeInsert(right$[x], z$);

Binary Search Trees: Insert

Insert element **not** in the tree.



Search for z. At some point the search stops at a null-pointer. This is the place to insert z.

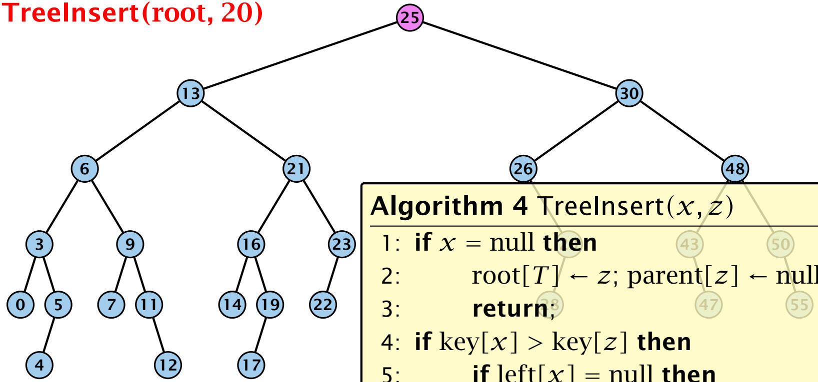
Algorithm 4 TreeInsert(x, z)

```
if x = null then
    root[T] ← z; parent[z] ← null;
    return;
if key[x] > key[z] then
    if left[x] = null then
        left[x] ← z; parent[z] ← x;
    else TreeInsert(left[x], z);
else
    if right[x] = null then
        right[x] ← z; parent[z] ← x;
    else TreeInsert(right[x], z);
```

Binary Search Trees: Insert

Insert element **not** in the tree.

TreeInsert(root, 20)



Algorithm 4 TreeInsert(x, z)

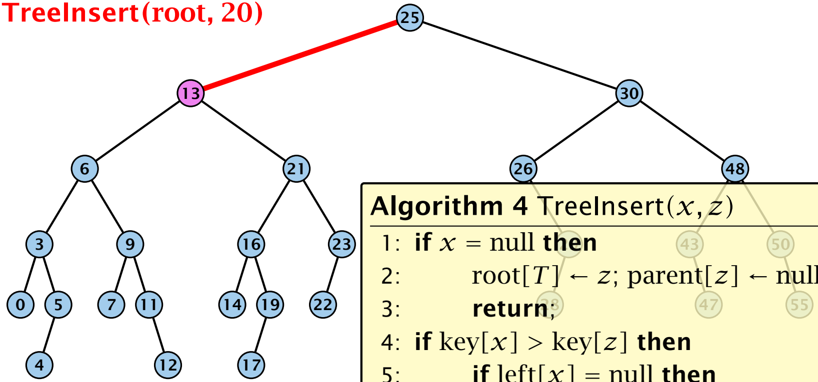
```
if x = null then
    root[T] ← z; parent[z] ← null;
    return;
if key[x] > key[z] then
    if left[x] = null then
        left[x] ← z; parent[z] ← x;
    else TreeInsert(left[x], z);
else
    if right[x] = null then
        right[x] ← z; parent[z] ← x;
    else TreeInsert(right[x], z);
```

Search for z. At some point the search stops at a null-pointer. This is the place to insert z.

Binary Search Trees: Insert

Insert element **not** in the tree.

TreeInsert(root, 20)



Search for z. At some point the search stops at a null-pointer. This is the place to insert z.

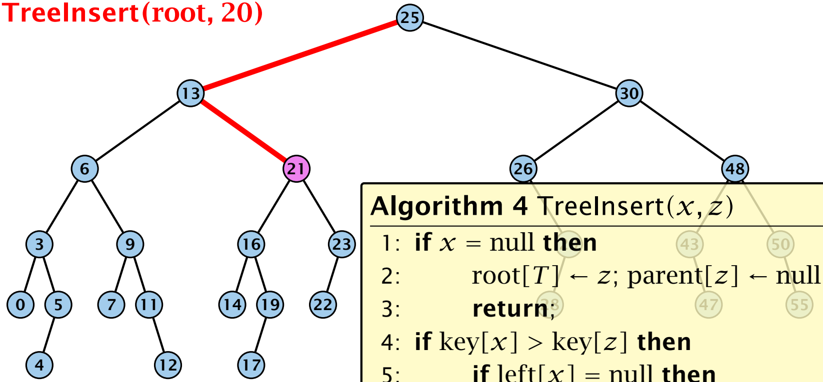
Algorithm 4 TreeInsert(x, z)

if $x = \text{null}$ **then**
    $\text{root}[T] \leftarrow z$; $\text{parent}[z] \leftarrow \text{null}$;
    return;
if $\text{key}[x] > \text{key}[z]$ **then**
    if $\text{left}[x] = \text{null}$ **then**
        $\text{left}[x] \leftarrow z$; $\text{parent}[z] \leftarrow x$;
    else TreeInsert$(\text{left}[x], z)$;
else
    if $\text{right}[x] = \text{null}$ **then**
        $\text{right}[x] \leftarrow z$; $\text{parent}[z] \leftarrow x$;
    else TreeInsert$(\text{right}[x], z)$;

Binary Search Trees: Insert

Insert element **not** in the tree.

TreeInsert(root, 20)



Algorithm 4 TreeInsert(x, z)

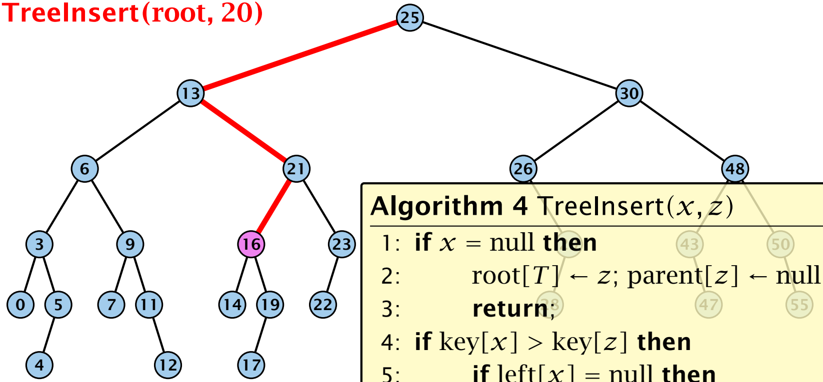
```
if x = null then
    root[T] ← z; parent[z] ← null;
    return;
if key[x] > key[z] then
    if left[x] = null then
        left[x] ← z; parent[z] ← x;
    else TreeInsert(left[x], z);
else
    if right[x] = null then
        right[x] ← z; parent[z] ← x;
    else TreeInsert(right[x], z);
```

Search for z. At some point the search stops at a null-pointer. This is the place to insert z.

Binary Search Trees: Insert

Insert element **not** in the tree.

TreeInsert(root, 20)



Search for z. At some point the search stops at a null-pointer. This is the place to insert z.

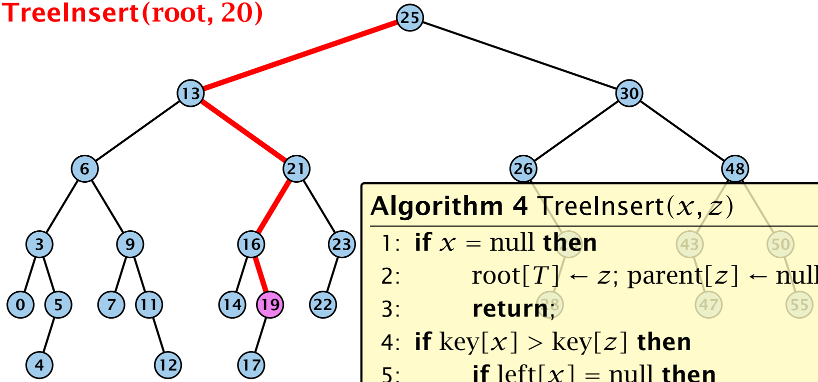
Algorithm 4 TreeInsert(x, z)

```
if x = null then
    root[T] ← z; parent[z] ← null;
    return;
if key[x] > key[z] then
    if left[x] = null then
        left[x] ← z; parent[z] ← x;
    else TreeInsert(left[x], z);
else
    if right[x] = null then
        right[x] ← z; parent[z] ← x;
    else TreeInsert(right[x], z);
```

Binary Search Trees: Insert

Insert element **not** in the tree.

TreeInsert(root, 20)



Search for z. At some point the search stops at a null-pointer. This is the place to insert z.

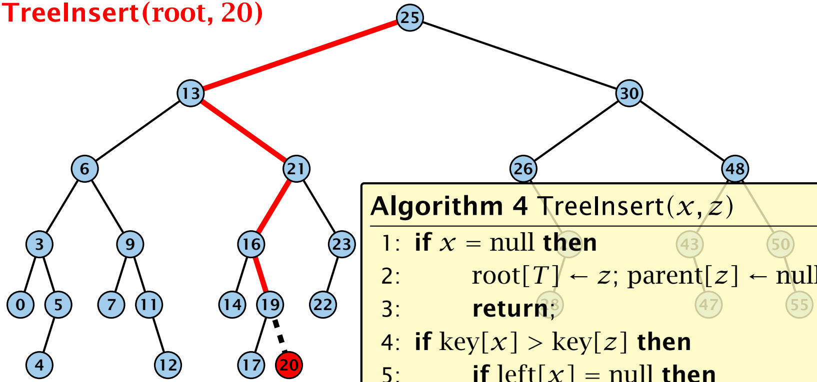
Algorithm 4 TreeInsert(x, z)

```
if x = null then
    root[T] ← z; parent[z] ← null;
    return;
if key[x] > key[z] then
    if left[x] = null then
        left[x] ← z; parent[z] ← x;
    else TreeInsert(left[x], z);
else
    if right[x] = null then
        right[x] ← z; parent[z] ← x;
    else TreeInsert(right[x], z);
```

Binary Search Trees: Insert

Insert element **not** in the tree.

TreeInsert(root, 20)

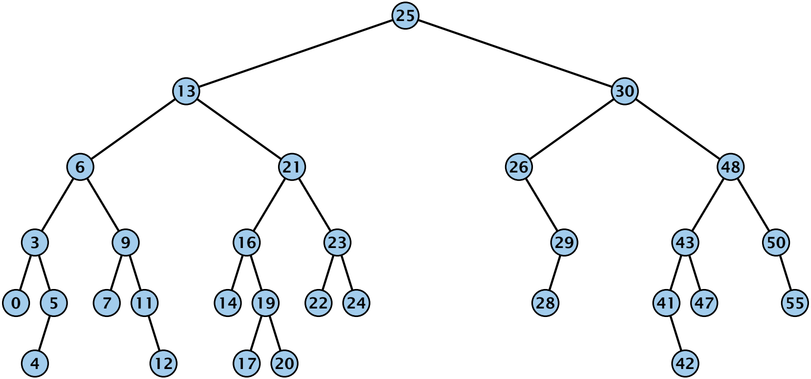


Search for z. At some point the search stops at a null-pointer. This is the place to insert z.

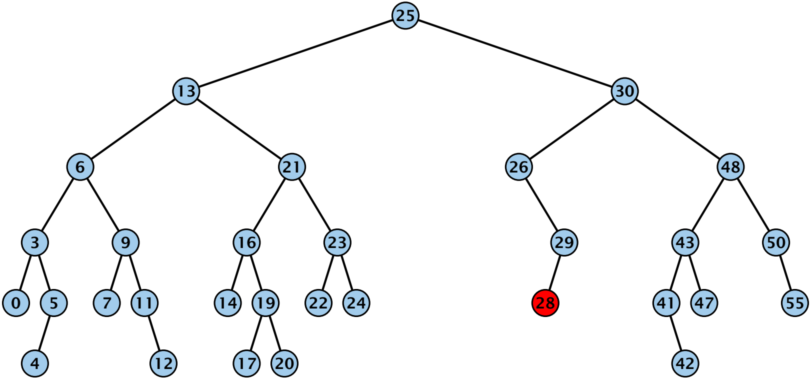
Algorithm 4 TreeInsert(x, z)

```
if x = null then
    root[T] ← z; parent[z] ← null;
    return;
if key[x] > key[z] then
    if left[x] = null then
        left[x] ← z; parent[z] ← x;
    else TreeInsert(left[x], z);
else
    if right[x] = null then
        right[x] ← z; parent[z] ← x;
    else TreeInsert(right[x], z);
```

Binary Search Trees: Delete



Binary Search Trees: Delete

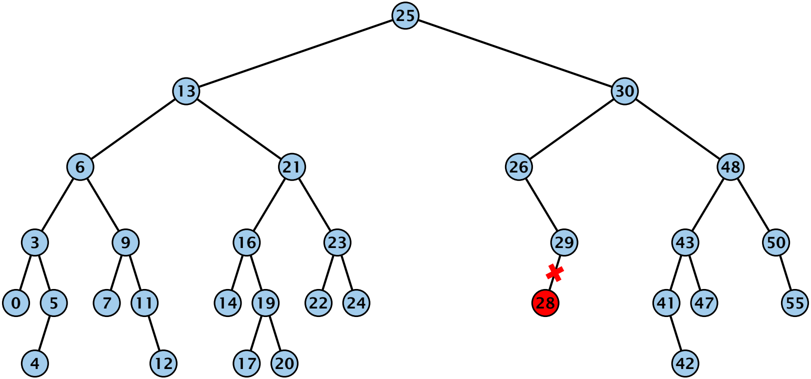


Case 1:

Element does not have any children

- Simply go to the parent and set the corresponding pointer to null.

Binary Search Trees: Delete

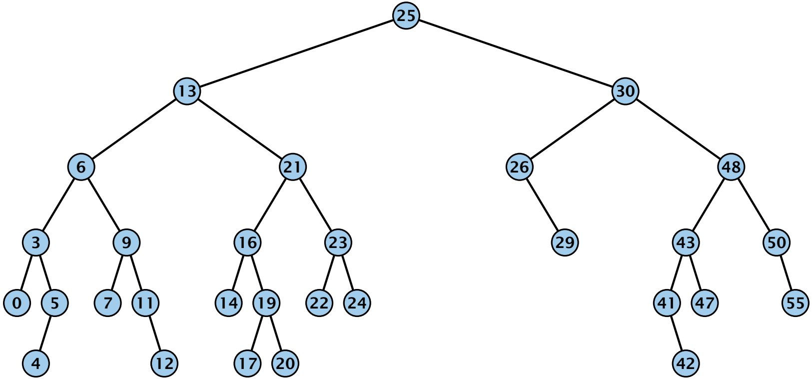


Case 1:

Element does not have any children

- Simply go to the parent and set the corresponding pointer to null.

Binary Search Trees: Delete

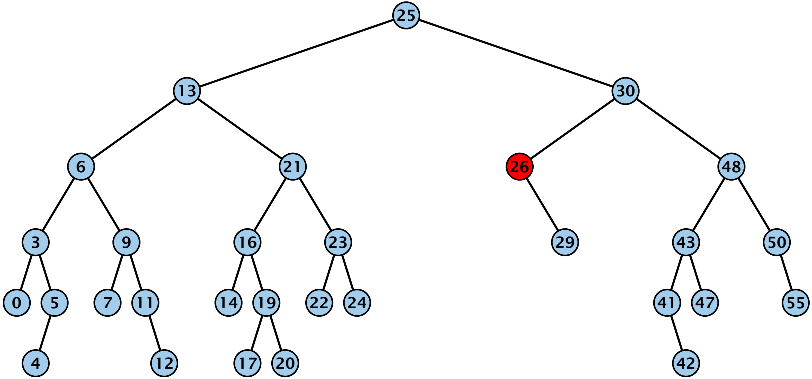


Case 1:

Element does not have any children

- Simply go to the parent and set the corresponding pointer to null.

Binary Search Trees: Delete

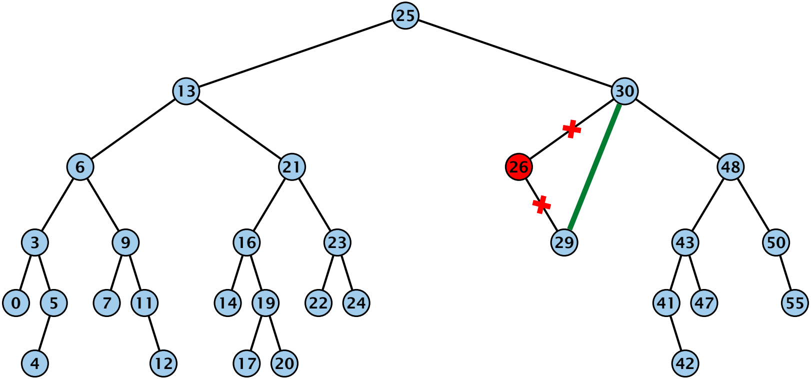


Case 2:

Element has exactly one child

- Splice the element out of the tree by connecting its parent to its successor.

Binary Search Trees: Delete

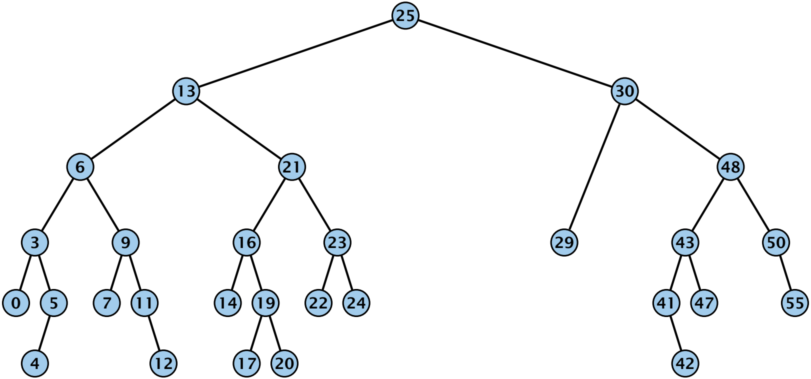


Case 2:

Element has exactly one child

- Splice the element out of the tree by connecting its parent to its successor.

Binary Search Trees: Delete

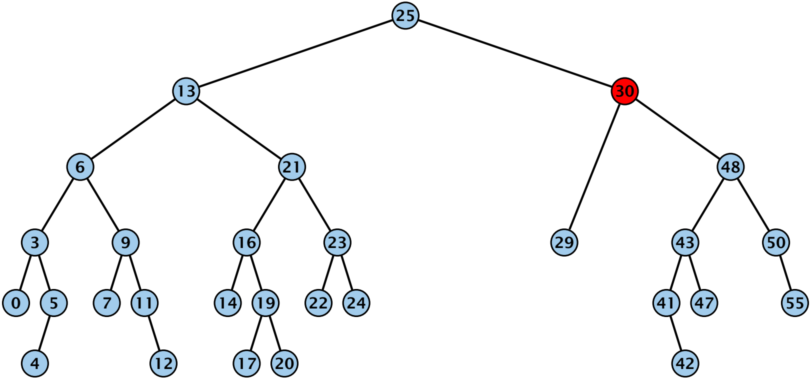


Case 2:

Element has exactly one child

- Splice the element out of the tree by connecting its parent to its successor.

Binary Search Trees: Delete

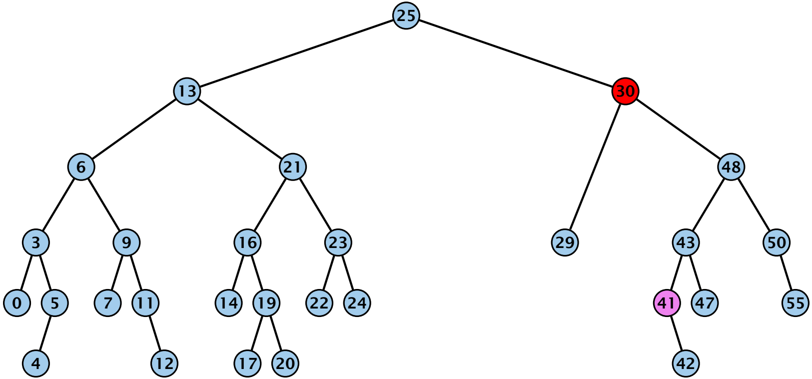


Case 3:

Element has two children

- Find the successor of the element
- Splice successor out of the tree
- Replace content of element by content of successor

Binary Search Trees: Delete

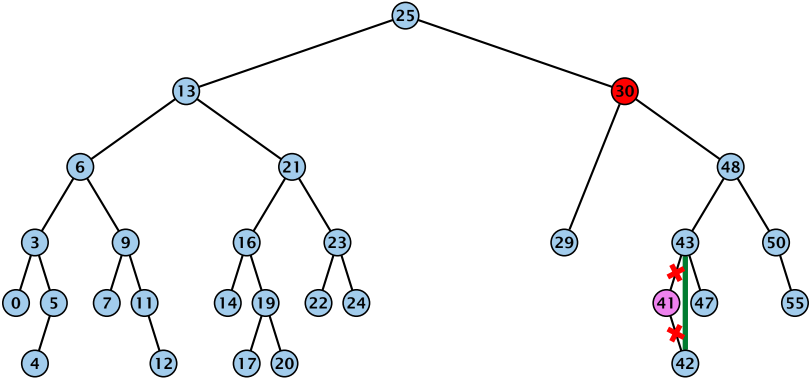


Case 3:

Element has two children

- Find the successor of the element
- Splice successor out of the tree
- Replace content of element by content of successor

Binary Search Trees: Delete

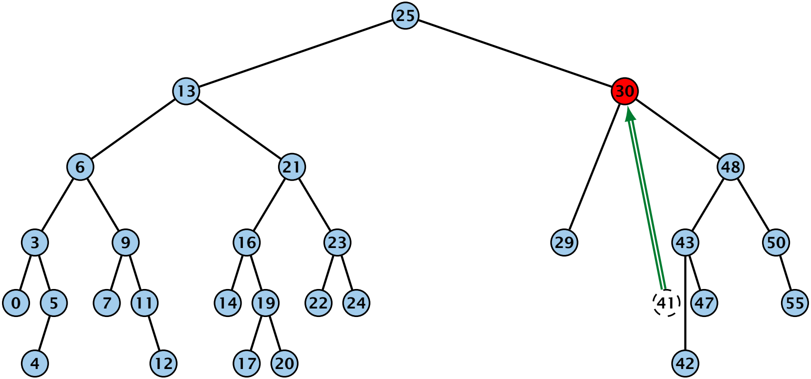


Case 3:

Element has two children

- Find the successor of the element
- Splice successor out of the tree
- Replace content of element by content of successor

Binary Search Trees: Delete

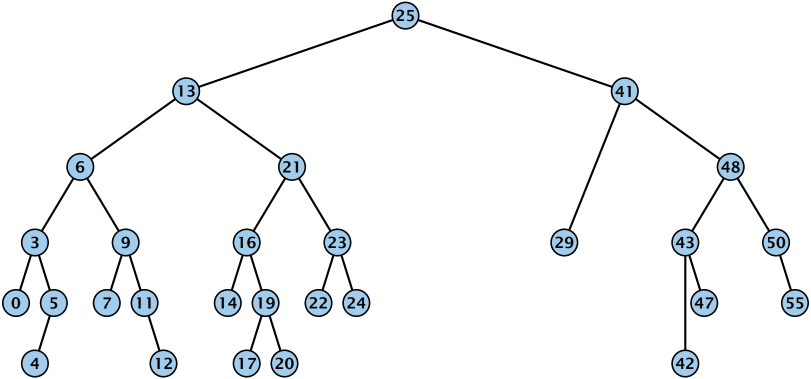


Case 3:

Element has two children

- Find the successor of the element
- Splice successor out of the tree
- Replace content of element by content of successor

Binary Search Trees: Delete

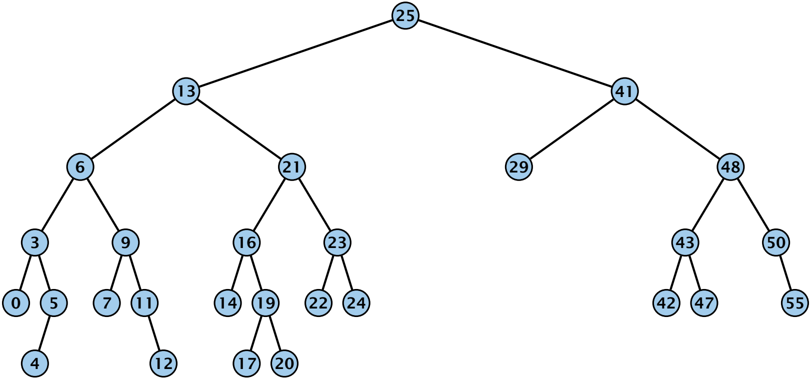


Case 3:

Element has two children

- Find the successor of the element
- Splice successor out of the tree
- Replace content of element by content of successor

Binary Search Trees: Delete



Case 3:

Element has two children

- Find the successor of the element
- Splice successor out of the tree
- Replace content of element by content of successor

Binary Search Trees: Delete

Algorithm 9 TreeDelete(z)

```
if left[z] = null or right[z] = null
    then y ← z else y ← TreeSucc(z);          select y to splice out
if left[y] ≠ null
    then x ← left[y] else x ← right[y];      x is child of y (or null)
if x ≠ null then parent[x] ← parent[y];      parent[x] is correct
if parent[y] = null then
    root[T] ← x
else
    if y = left[parent[y]] then               fix pointer to x
        left[parent[y]] ← x
    else
        right[parent[y]] ← x
if y ≠ z then copy y-data to z
```

Balanced Binary Search Trees

All operations on a binary search tree can be performed in time $\mathcal{O}(h)$, where h denotes the height of the tree.

However the height of the tree may become as large as $\Theta(n)$.

Balanced Binary Search Trees
With each insert- and delete-operation perform local adjustments to guarantee a height of $\mathcal{O}(\log n)$.

AVL-trees, Red-black trees, Scapegoat trees, 2-3 trees, B-trees, AA trees, Treaps

similar: SPLAY trees.

Balanced Binary Search Trees

All operations on a binary search tree can be performed in time $\mathcal{O}(h)$, where h denotes the height of the tree.

However the height of the tree may become as large as $\Theta(n)$.

Balanced Binary Search Trees
With each insert- and delete-operation perform local adjustments to guarantee a height of $\mathcal{O}(\log n)$.

AVL-trees, Red-black trees, Scapegoat trees, 2-3 trees, B-trees, AA trees, Treaps

similar: SPLAY trees.

Balanced Binary Search Trees

All operations on a binary search tree can be performed in time $\mathcal{O}(h)$, where h denotes the height of the tree.

However the height of the tree may become as large as $\Theta(n)$.

Balanced Binary Search Trees
With each insert- and delete-operation perform local adjustments to guarantee a height of $\mathcal{O}(\log n)$.

AVL-trees, Red-black trees, Scapegoat trees, 2-3 trees, B-trees, AA trees, Treaps

similar: SPLAY trees.

Balanced Binary Search Trees

All operations on a binary search tree can be performed in time $\mathcal{O}(h)$, where h denotes the height of the tree.

However the height of the tree may become as large as $\Theta(n)$.

Balanced Binary Search Trees
With each insert- and delete-operation perform local adjustments to guarantee a height of $\mathcal{O}(\log n)$.

AVL-trees, Red-black trees, Scapegoat trees, 2-3 trees, B-trees, AA trees, Treaps

similar: SPLAY trees.

Balanced Binary Search Trees

All operations on a binary search tree can be performed in time $\mathcal{O}(h)$, where h denotes the height of the tree.

However the height of the tree may become as large as $\Theta(n)$.

Balanced Binary Search Trees
With each insert- and delete-operation perform local adjustments to guarantee a height of $\mathcal{O}(\log n)$.

AVL-trees, Red-black trees, Scapegoat trees, 2-3 trees, B-trees, AA trees, Treaps

similar: SPLAY trees.