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3.2 BINARY SEARCH TREES

- ▶ *BSTs*
- ▶ *ordered operations*
- ▶ *deletion*



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3.2 BINARY SEARCH TREES

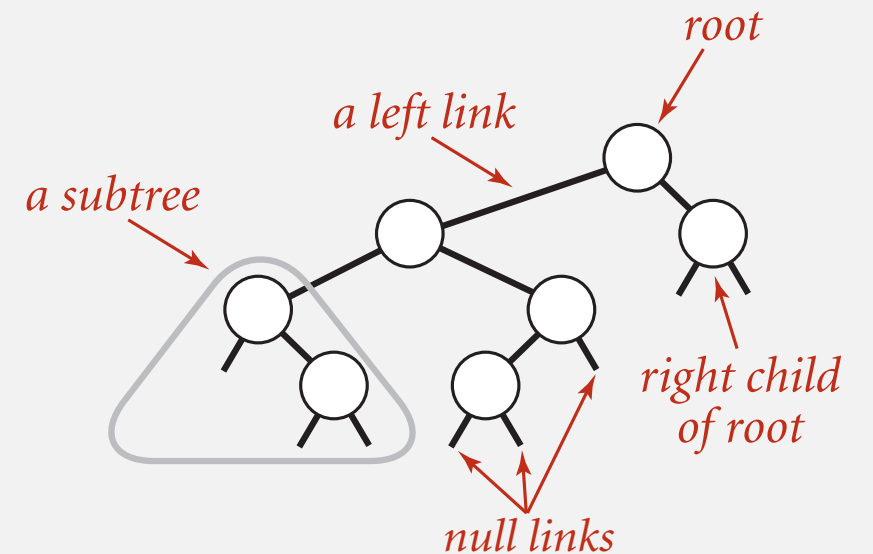
- ▶ *BSTs*
- ▶ *ordered operations*
- ▶ *deletion*

Binary search trees

Definition. A BST is a **binary tree** in **symmetric order**.

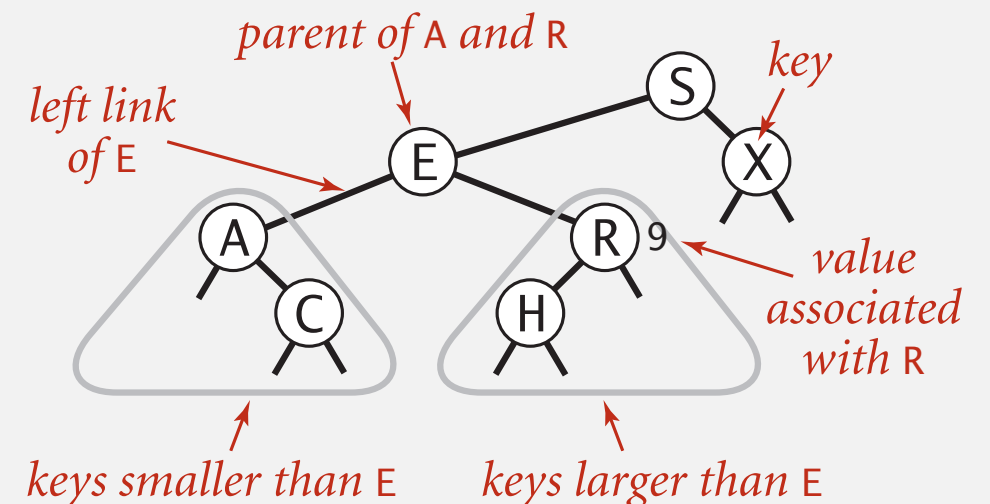
A binary tree is either:

- Empty.
- Two disjoint binary trees (left and right).



Symmetric order. Each node has a key, and every node's key is:

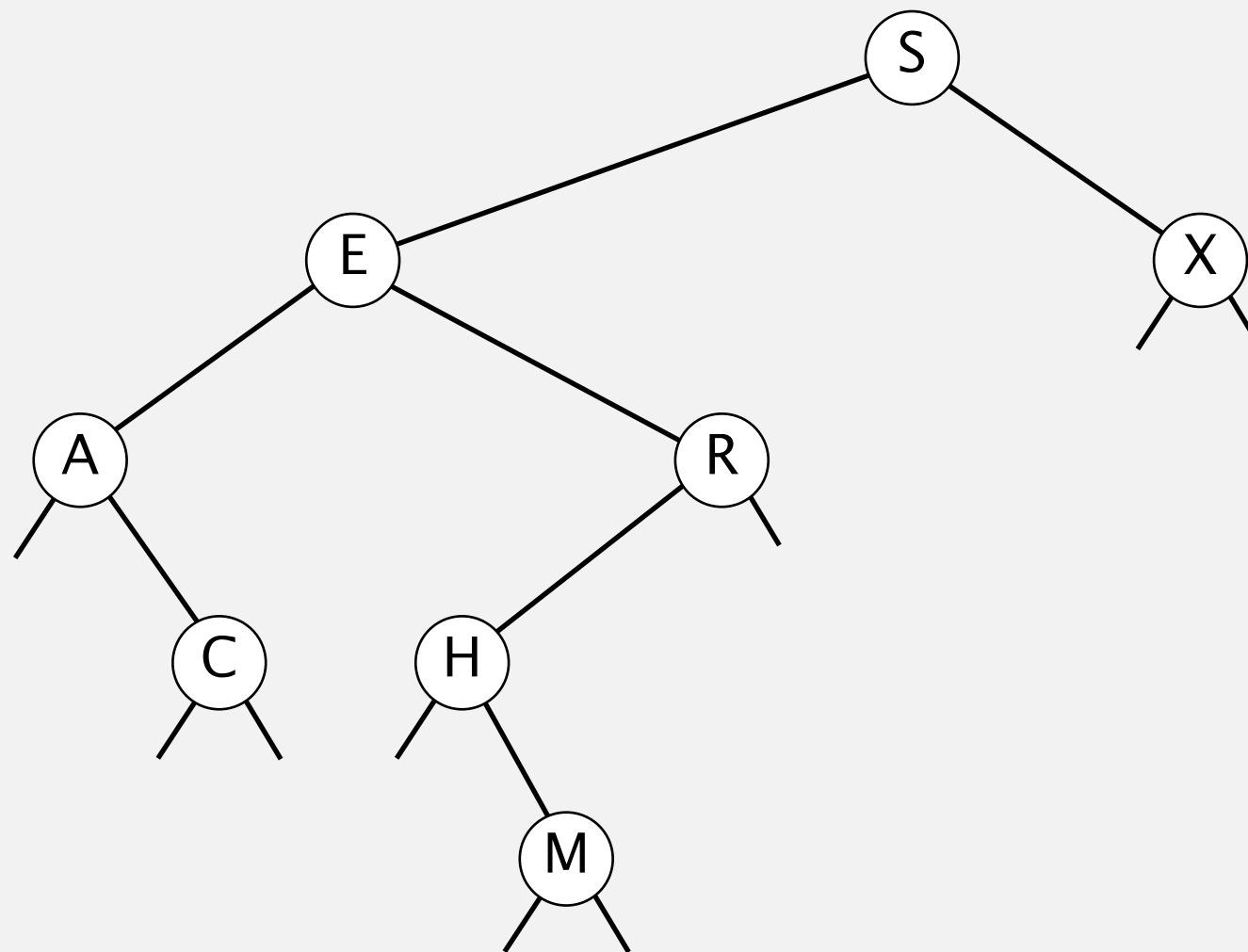
- Larger than all keys in its left subtree.
- Smaller than all keys in its right subtree.



Binary search tree demo

Search. If less, go left; if greater, go right; if equal, search hit.

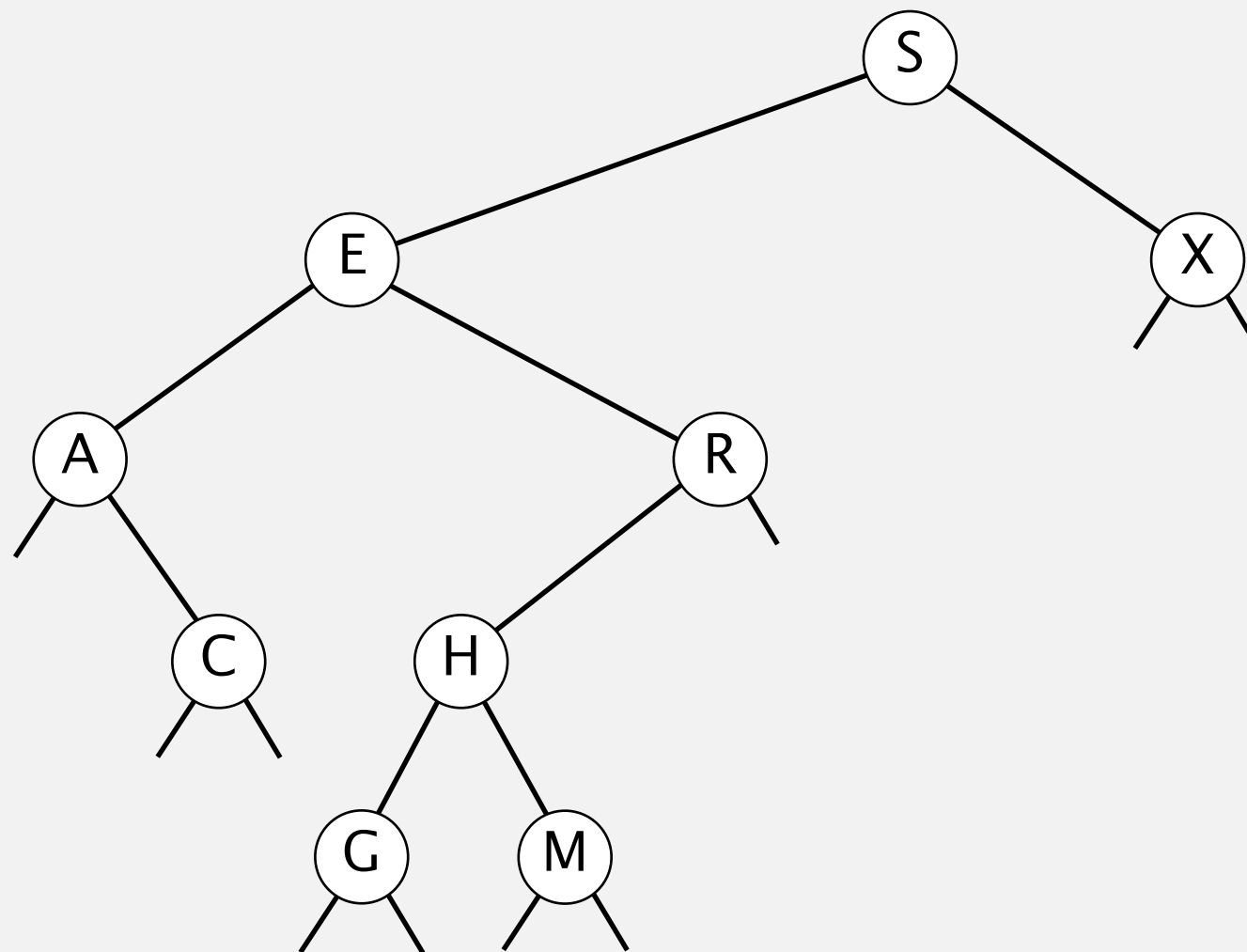
successful search for H



Binary search tree demo

Insert. If less, go left; if greater, go right; if null, insert.

insert G



BST representation in Java

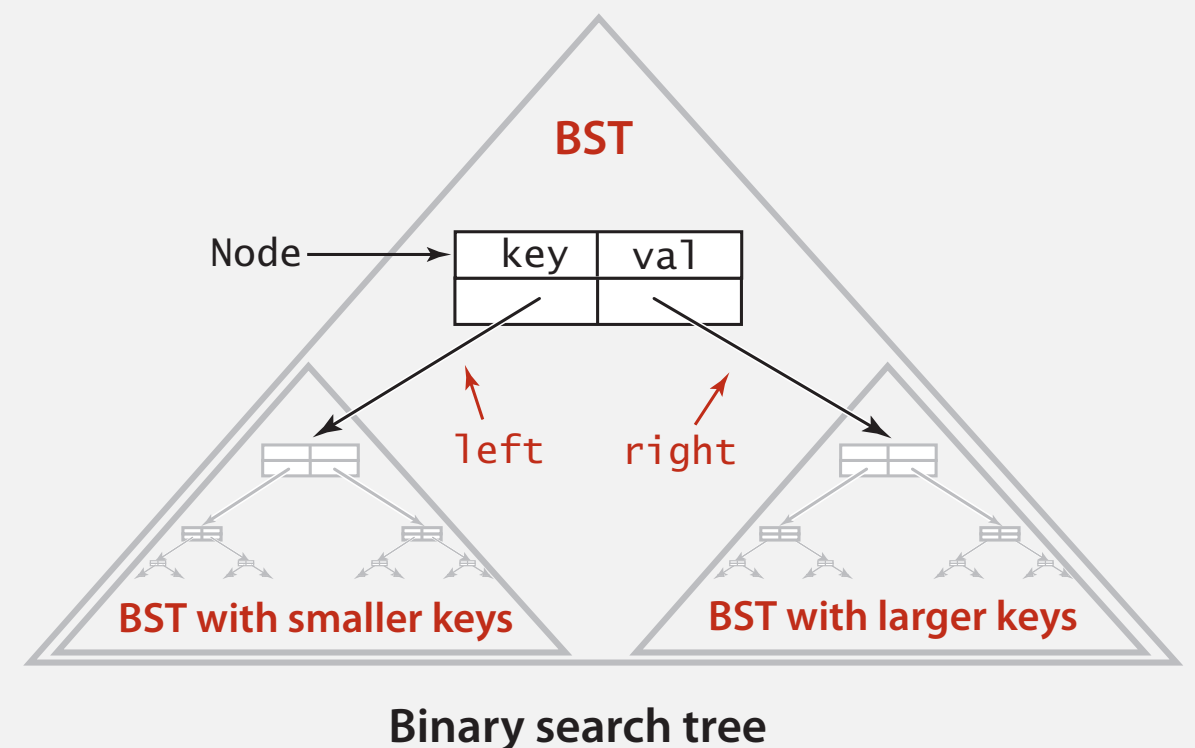
Java definition. A BST is a reference to a root Node.

A Node is composed of four fields:

- A Key and a Value.
- A reference to the left and right subtree.

↑ smaller keys ↑ larger keys

```
private class Node
{
    private Key key;
    private Value val;
    private Node left, right;
    public Node(Key key, Value val)
    {
        this.key = key;
        this.val = val;
    }
}
```



Key and Value are generic types; Key is Comparable

BST implementation (skeleton)

```
public class BST<Key extends Comparable<Key>, Value>  
{
```

```
    private Node root;
```

← root of BST

```
    private class Node  
    { /* see previous slide */ }
```

```
    public void put(Key key, Value val)  
    { /* see next slides */ }
```

```
    public Value get(Key key)  
    { /* see next slides */ }
```

```
    public void delete(Key key)  
    { /* see next slides */ }
```

```
    public Iterable<Key> iterator()  
    { /* see next slides */ }
```

```
}
```

BST search: Java implementation

Get. Return value corresponding to given key, or null if no such key.

```
public Value get(Key key)
{
    Node x = root;
    while (x != null)
    {
        int cmp = key.compareTo(x.key);
        if      (cmp < 0) x = x.left;
        else if (cmp > 0) x = x.right;
        else if (cmp == 0) return x.val;
    }
    return null;
}
```

Cost. Number of compares is equal to 1 + depth of node.

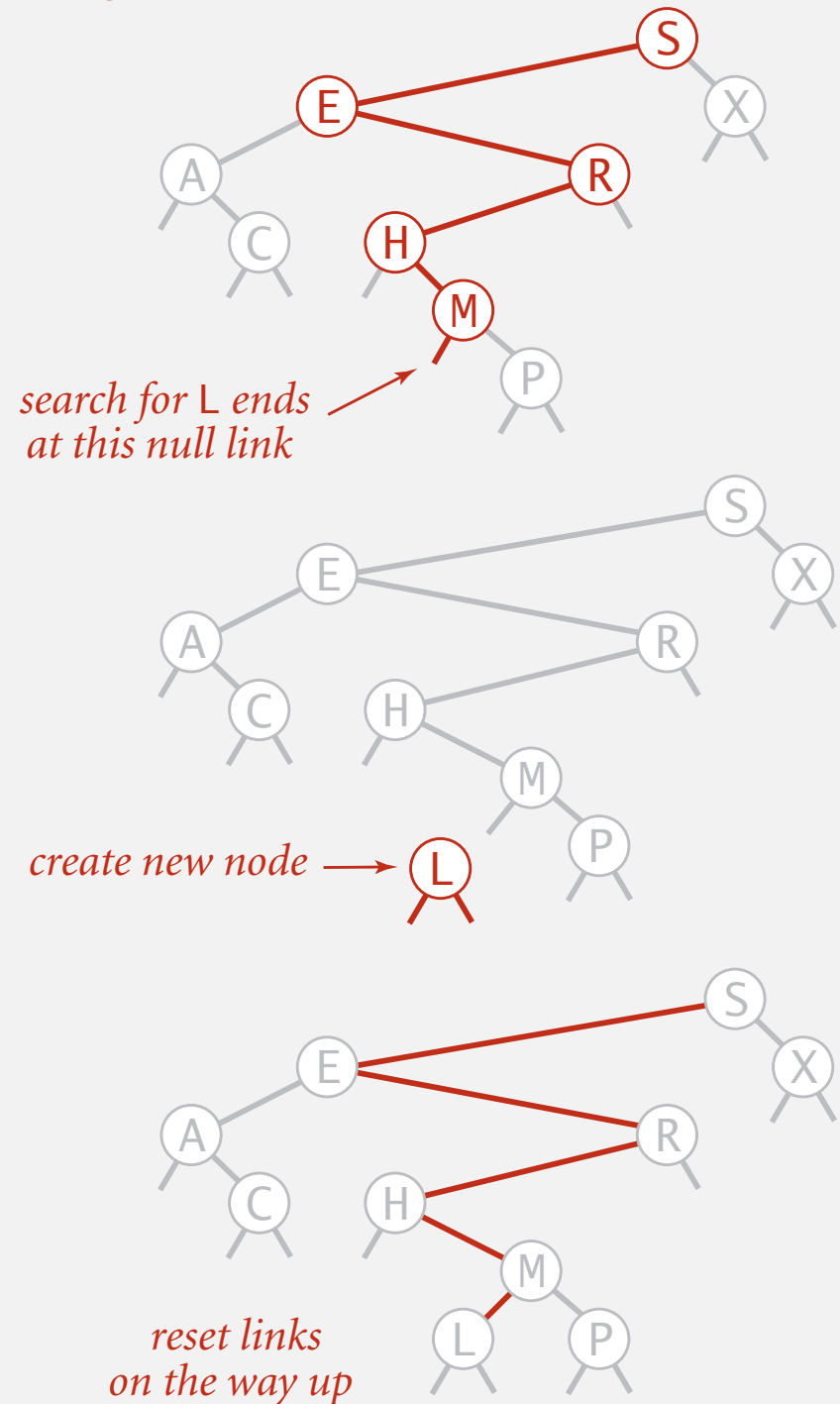
BST insert

Put. Associate value with key.

Search for key, then two cases:

- Key in tree \Rightarrow reset value.
- Key not in tree \Rightarrow add new node.

inserting L



Insertion into a BST

BST insert: Java implementation

Put. Associate value with key.

```
public void put(Key key, Value val)
{   root = put(root, key, val);   }

private Node put(Node x, Key key, Value val)
{
    if (x == null) return new Node(key, val);
    int cmp = key.compareTo(x.key);
    if      (cmp < 0)
        x.left  = put(x.left,  key, val);
    else if (cmp > 0)
        x.right = put(x.right, key, val);
    else if (cmp == 0)
        x.val = val;
    return x;
}
```

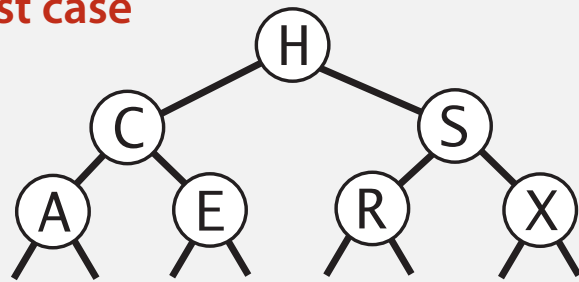
concise, but tricky,
recursive code;
read carefully!

Cost. Number of compares is equal to 1 + depth of node.

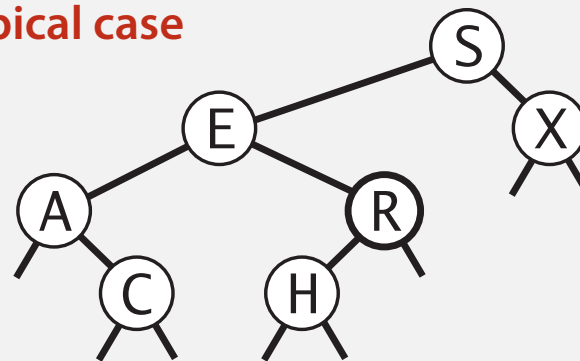
Tree shape

- Many BSTs correspond to same set of keys.
- Number of compares for search/insert is equal to $1 + \text{depth of node}$.

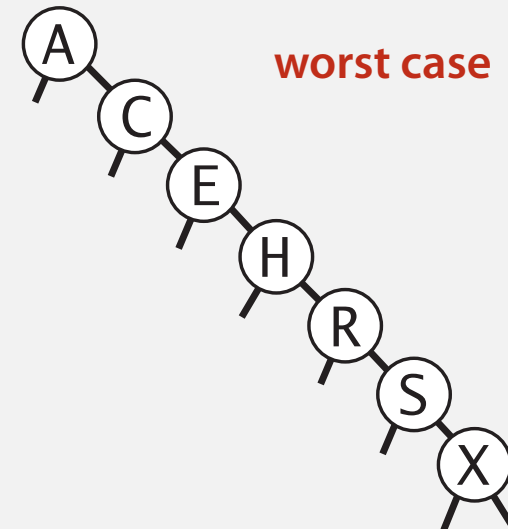
best case



typical case



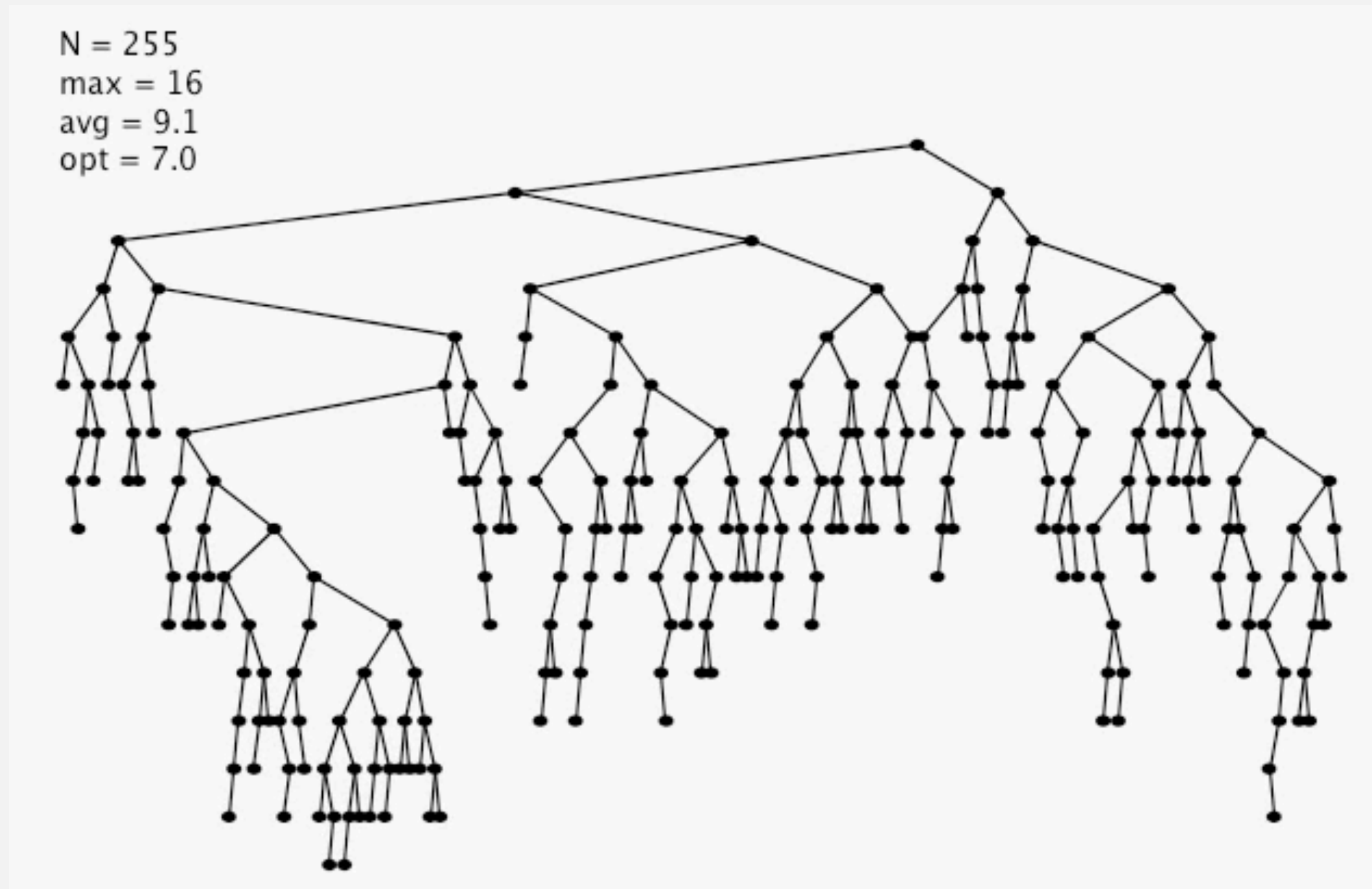
worst case



Bottom line. Tree shape depends on order of insertion.

BST insertion: random order visualization

Ex. Insert keys in random order.



Sorting with a binary search tree

Q. What is this sorting algorithm?

0. Shuffle the array of keys.
1. Insert all keys into a BST.
2. Do an inorder traversal of BST.

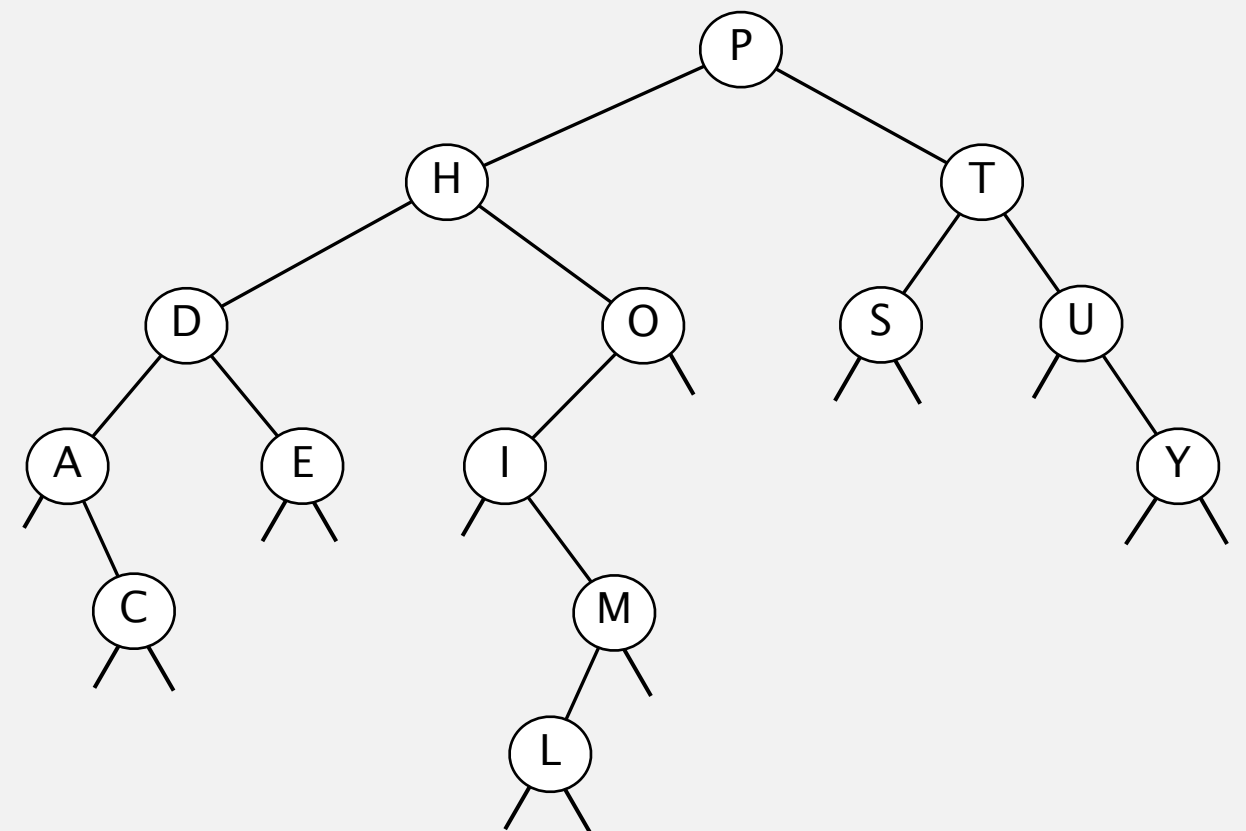
A. It's not a sorting algorithm (if there are duplicate keys)!

Q. OK, so what if there are no duplicate keys?

Q. What are its properties?

Correspondence between BSTs and quicksort partitioning

0	1	2	3	4	5	6	7	8	9	10	11	12	13
P	S	E	U	D	O	M	Y	T	H	I	C	A	L
P	S	E	U	D	O	M	Y	T	H	I	C	A	L
H	L	E	A	D	O	M	C	I	P	T	Y	U	S
D	C	E	A	H	O	M	L	I	P	T	Y	U	S
A	C	D	E	H	O	M	L	I	P	T	Y	U	S
A	C	D	E	H	O	M	L	I	P	T	Y	U	S
A	C	D	E	H	O	M	L	I	P	T	Y	U	S
A	C	D	E	H	O	M	L	I	P	T	Y	U	S
A	C	D	E	H	I	M	L	O	P	T	Y	U	S
A	C	D	E	H	I	M	L	O	P	T	Y	U	S
A	C	D	E	H	I	L	M	O	P	T	Y	U	S
A	C	D	E	H	I	L	M	O	P	S	T	U	Y
A	C	D	E	H	I	L	M	O	P	S	T	U	Y
A	C	D	E	H	I	L	M	O	P	S	T	U	Y
A	C	D	E	H	I	L	M	O	P	S	T	U	Y
A	C	D	E	H	I	L	M	O	P	S	T	U	Y



Remark. Correspondence is 1–1 if array has no duplicate keys.

BSTs: mathematical analysis

Proposition. If N distinct keys are inserted into a BST in **random** order, the expected number of compares for a search/insert is $\sim 2 \ln N$.

Pf. 1–1 correspondence with quicksort partitioning.

Proposition. [Reed, 2003] If N distinct keys are inserted in random order, expected height of tree is $\sim 4.311 \ln N$.

How Tall is a Tree?

Bruce Reed
CNRS, Paris, France
reed@moka.ccr.jussieu.fr

ABSTRACT

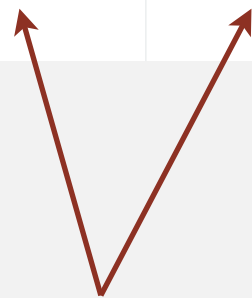
Let H_n be the height of a random binary search tree on n nodes. We show that there exists constants $\alpha = 4.31107\dots$ and $\beta = 1.95\dots$ such that $\mathbf{E}(H_n) = \alpha \log n - \beta \log \log n + O(1)$. We also show that $\text{Var}(H_n) = O(1)$.

But... Worst-case height is N .

[exponentially small chance when keys are inserted in random order]

ST implementations: summary

implementation	guarantee		average case		operations on keys
	search	insert	search hit	insert	
sequential search (unordered list)	N	N	$\frac{1}{2} N$	N	<code>equals()</code>
binary search (ordered array)	$\lg N$	N	$\lg N$	$\frac{1}{2} N$	<code>compareTo()</code>
BST	N	N	$1.39 \lg N$	$1.39 \lg N$	<code>compareTo()</code>



Why not shuffle to ensure a (probabilistic) guarantee of $4.311 \ln N$?



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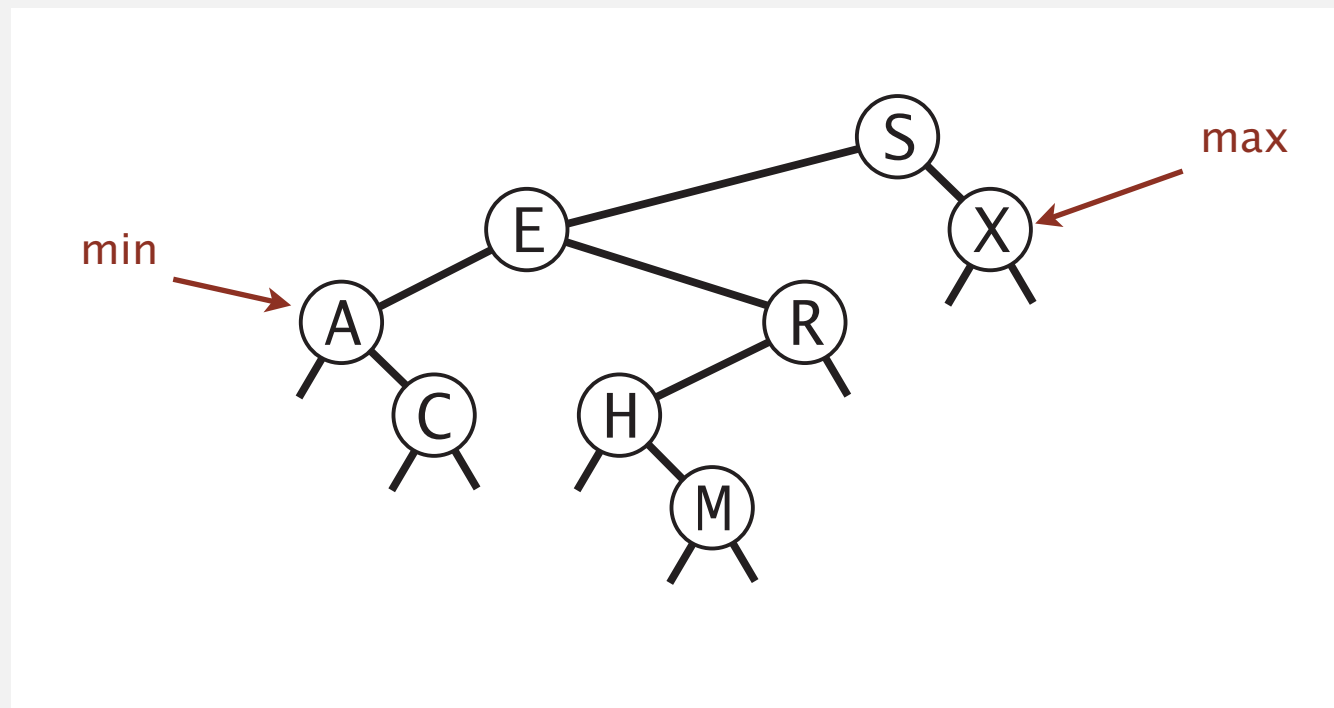
3.2 BINARY SEARCH TREES

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Minimum and maximum

Minimum. Smallest key in table.

Maximum. Largest key in table.

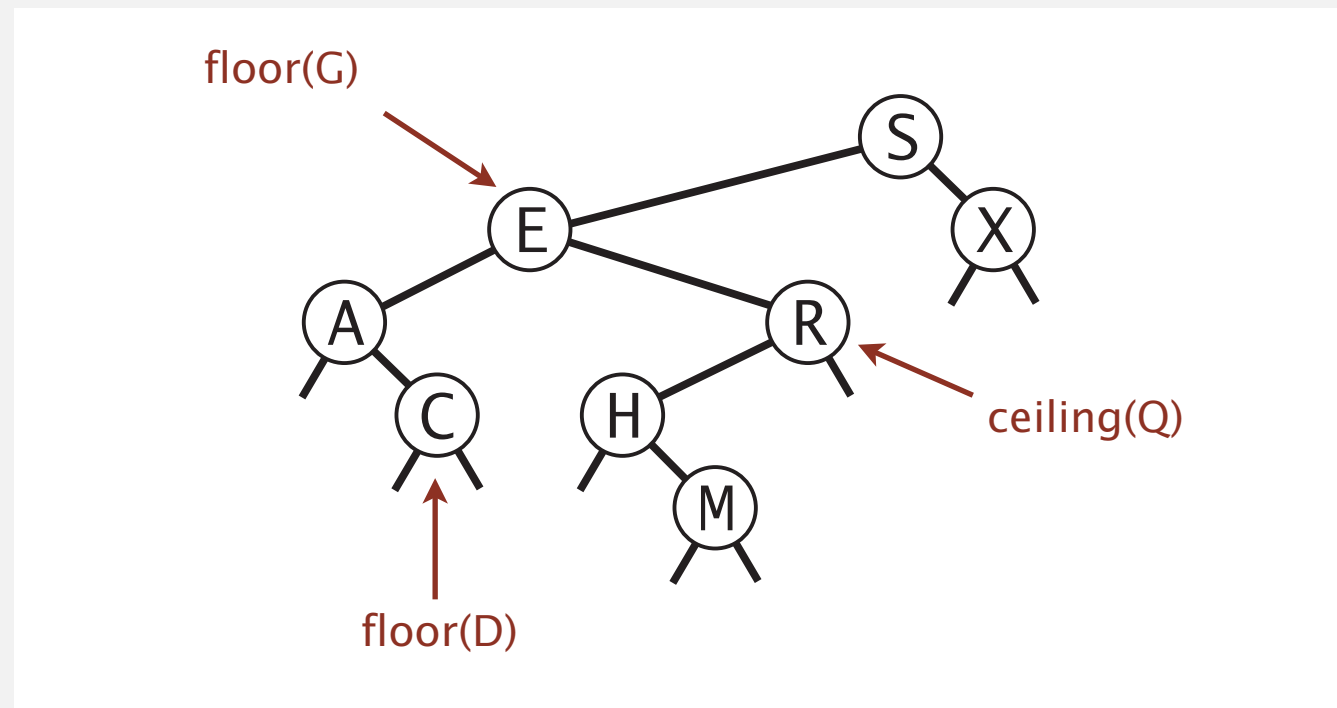


Q. How to find the min / max?

Floor and ceiling

Floor. Largest key \leq a given key.

Ceiling. Smallest key \geq a given key.



Q. How to find the floor / ceiling?

Computing the floor

Case 1. [k equals the key in the node]

The floor of k is k .

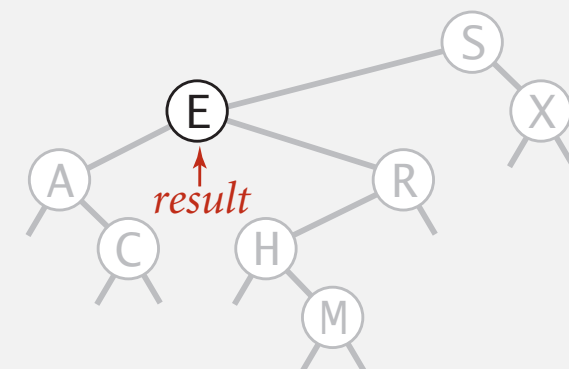
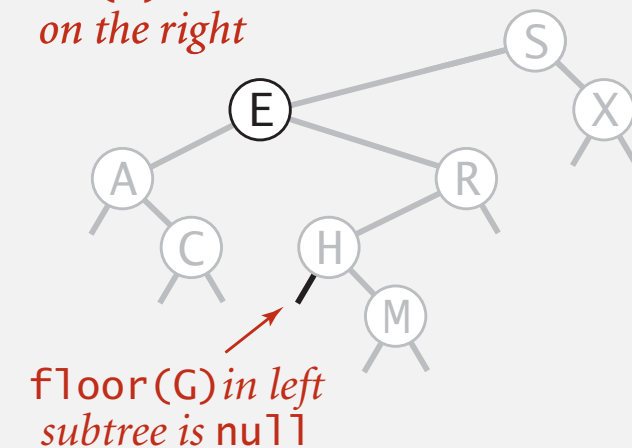
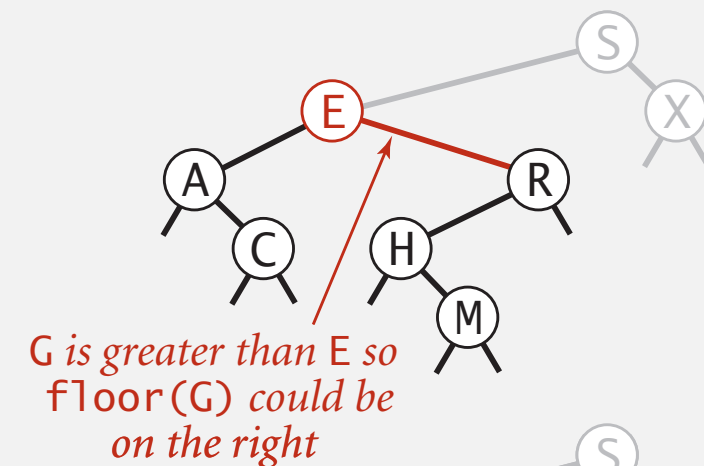
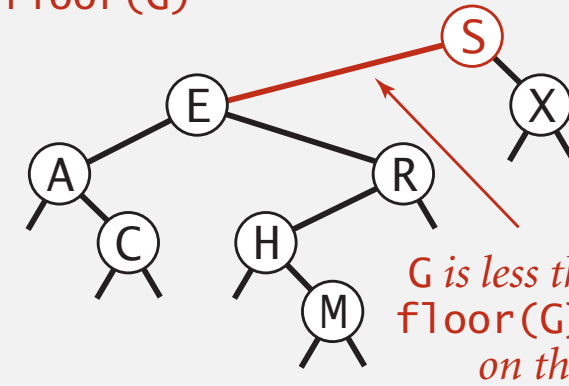
Case 2. [k is less than the key in the node]

The floor of k is in the left subtree.

Case 3. [k is greater than the key in the node]

The floor of k is in the right subtree
(if there is any key $\leq k$ in right subtree);
otherwise it is the key in the node.

finding floor(G)



Computing the floor

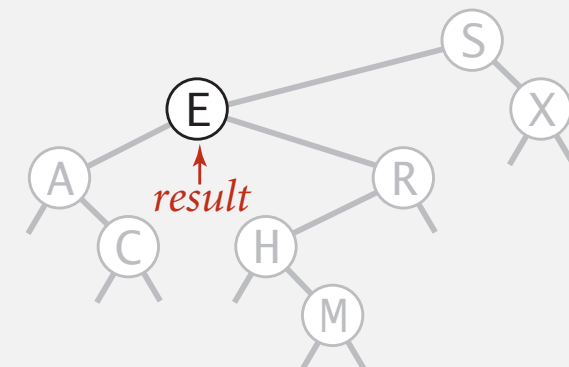
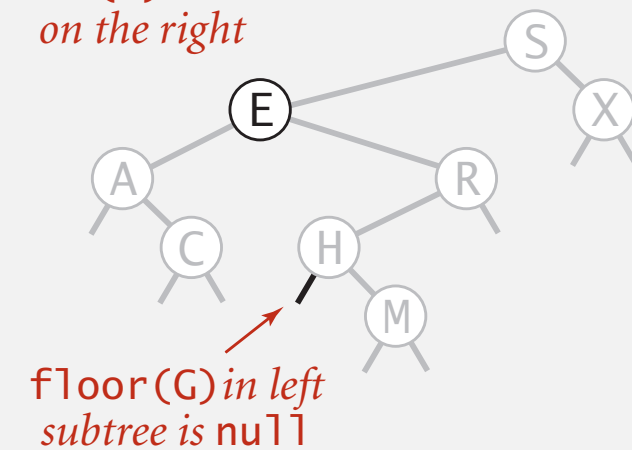
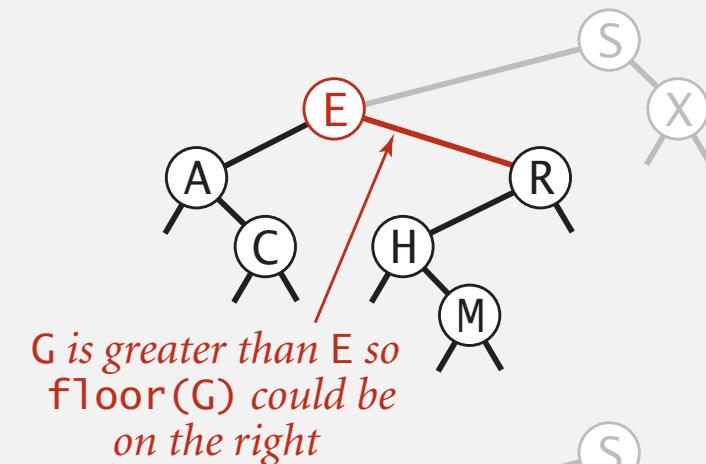
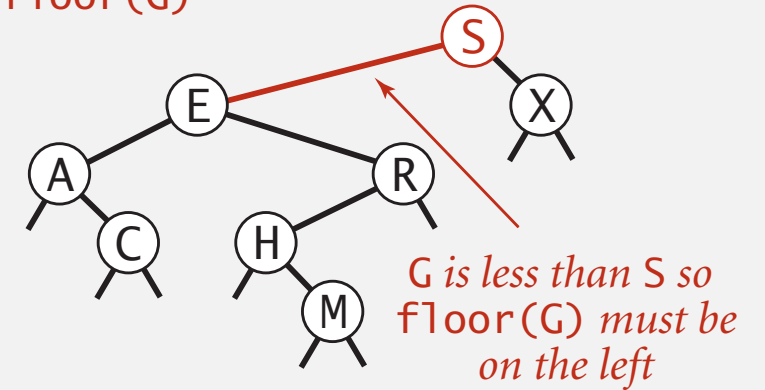
```
public Key floor(Key key)
{
    Node x = floor(root, key);
    if (x == null) return null;
    return x.key;
}
private Node floor(Node x, Key key)
{
    if (x == null) return null;
    int cmp = key.compareTo(x.key);

    if (cmp == 0) return x;

    if (cmp < 0) return floor(x.left, key);

    Node t = floor(x.right, key);
    if (t != null) return t;
    else return x;
}
```

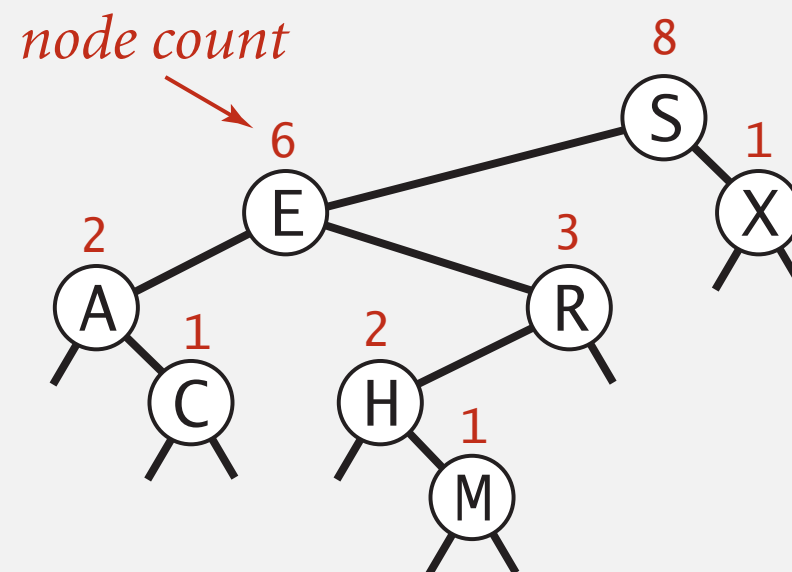
finding floor(G)



Rank and select


Q. How to implement `rank()` and `select()` efficiently?

A. In each node, we store the number of nodes in the subtree rooted at that node; to implement `size()`, return the count at the root.



BST implementation: subtree counts


```
private class Node
{
    private Key key;
    private Value val;
    private Node left;
    private Node right;
    private int count;
}
```



number of nodes in subtree


```
public int size()
{ return size(root); }
```

```
private int size(Node x)
{
    if (x == null) return 0;
    return x.count;
}
```



ok to call
when x is null

```
private Node put(Node x, Key key, Value val)
{
    if (x == null) return new Node(key, val, 1);
    int cmp = key.compareTo(x.key);
    if (cmp < 0) x.left = put(x.left, key, val);
    else if (cmp > 0) x.right = put(x.right, key, val);
    else if (cmp == 0) x.val = val;
    x.count = 1 + size(x.left) + size(x.right);
    return x;
}
```

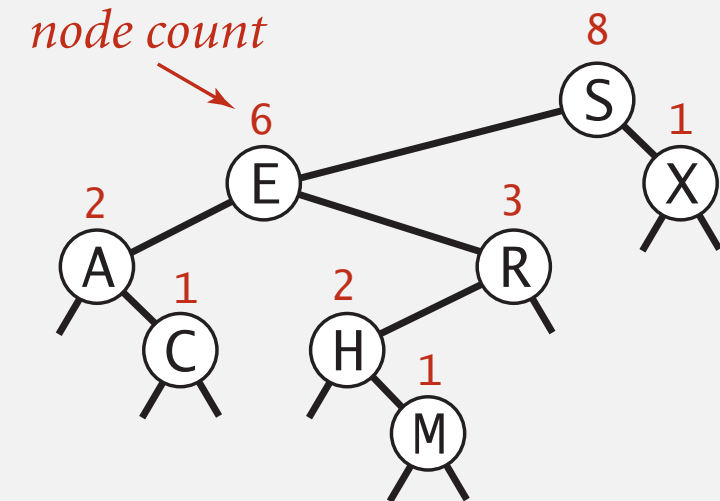


initialize subtree
count to 1

Rank

Rank. How many keys $< k$?

Easy recursive algorithm (3 cases!)



```
public int rank(Key key)
{ return rank(key, root); }
```

```
private int rank(Key key, Node x)
{
```

```
    if (x == null) return 0;
    int cmp = key.compareTo(x.key);
    if (cmp < 0) return rank(key, x.left);
    else if (cmp > 0) return 1 + size(x.left) + rank(key, x.right);
    else if (cmp == 0) return size(x.left);
```

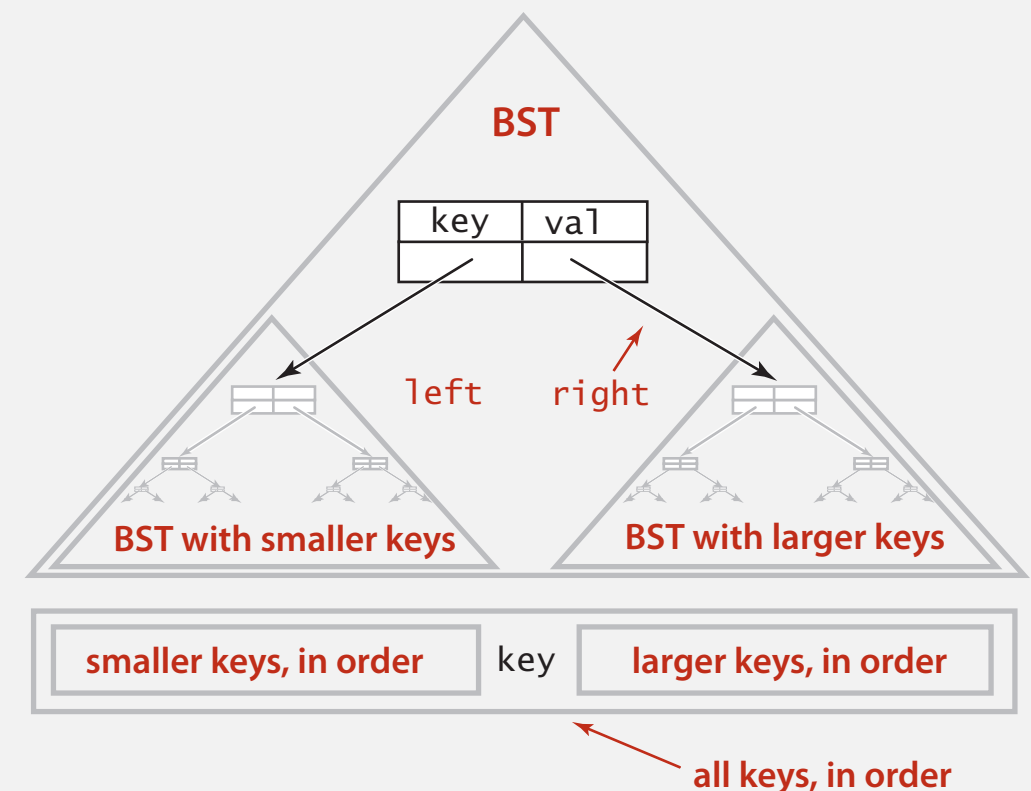
```
}
```


Inorder traversal

- Traverse left subtree.
- Enqueue key.
- Traverse right subtree.

```
public Iterable<Key> keys()
{
    Queue<Key> q = new Queue<Key>();
    inorder(root, q);
    return q;
}

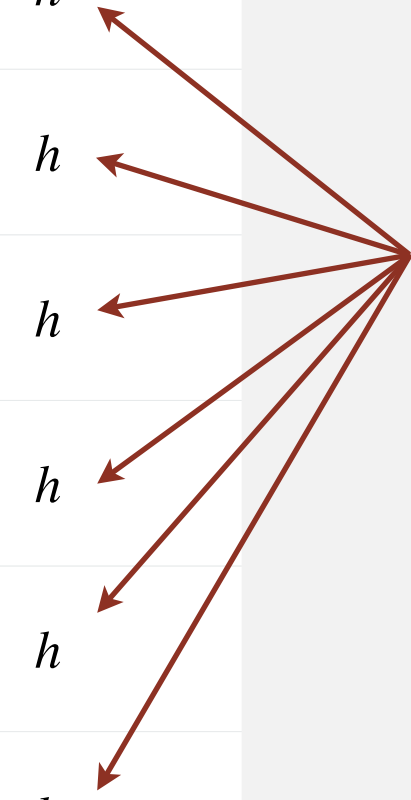
private void inorder(Node x, Queue<Key> q)
{
    if (x == null) return;
    inorder(x.left, q);
    q.enqueue(x.key);
    inorder(x.right, q);
}
```



Property. Inorder traversal of a BST yields keys in ascending order.

BST: ordered symbol table operations summary

	sequential search	binary search	BST
search	N	$\lg N$	h
insert	N	N	h
min / max	N	1	h
floor / ceiling	N	$\lg N$	h
rank	N	$\lg N$	h
select	N	1	h



h = height of BST
(proportional to $\log N$
if keys inserted in random order)

order of growth of running time of ordered symbol table operations



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3.2 BINARY SEARCH TREES

- ▶ *BSTs*
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- ▶ *deletion*

ST implementations: summary

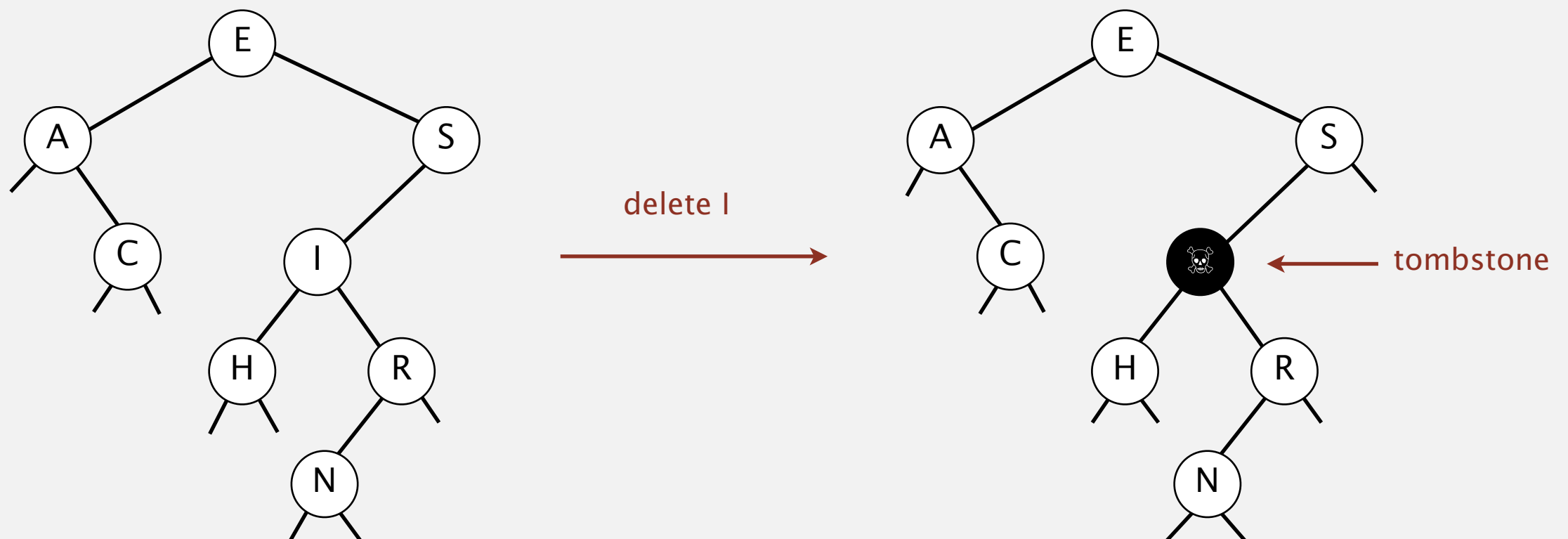
implementation	guarantee			average case			ordered ops?	operations on keys
	search	insert	delete	search hit	insert	delete		
sequential search (linked list)	N	N	N	$\frac{1}{2} N$	N	$\frac{1}{2} N$		<code>equals()</code>
binary search (ordered array)	$\lg N$	N	N	$\lg N$	$\frac{1}{2} N$	$\frac{1}{2} N$	✓	<code>compareTo()</code>
BST	N	N	N	$1.39 \lg N$	$1.39 \lg N$???	✓	<code>compareTo()</code>

Next. Deletion in BSTs.

BST deletion: lazy approach

To remove a node with a given key:

- Set its value to null.
- Leave key in tree to guide search (but don't consider it equal in search).



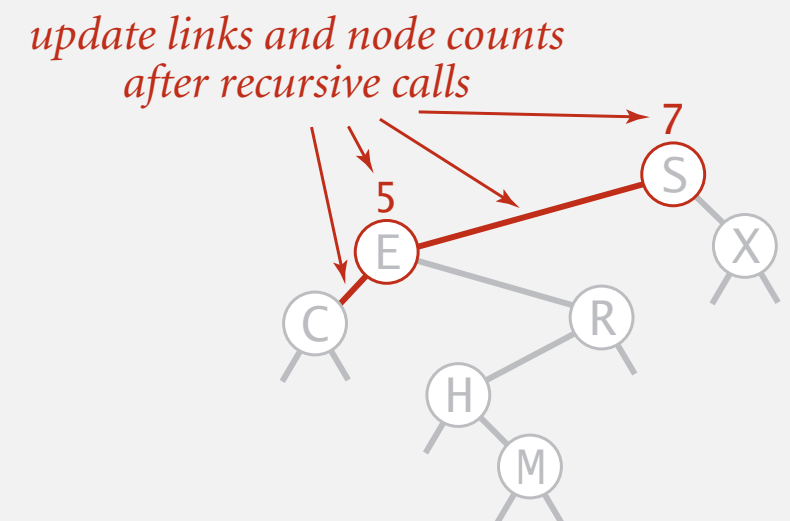
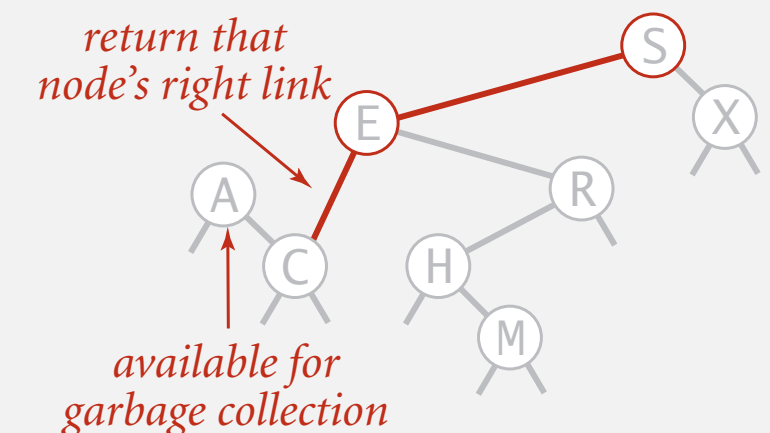
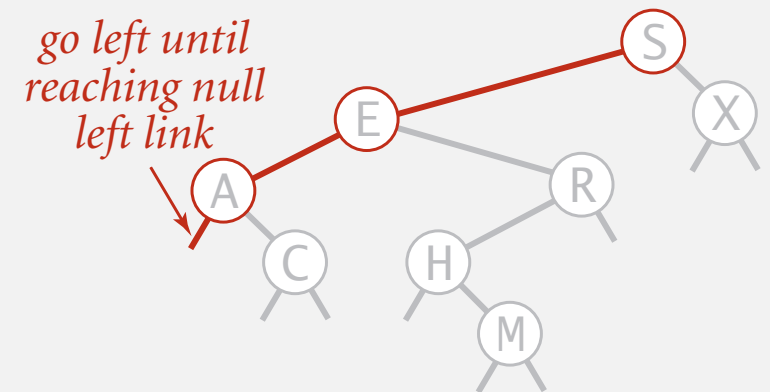
Cost. $\sim 2 \ln N'$ per insert, search, and delete (if keys in random order), where N' is the number of key-value pairs ever inserted in the BST.

Unsatisfactory solution. Tombstone (memory) overload.

Deleting the minimum

To delete the minimum key:

- Go left until finding a node with a null left link.
- Replace that node by its right link.
- Update subtree counts.



```
public void deleteMin()
{  root = deleteMin(root);  }

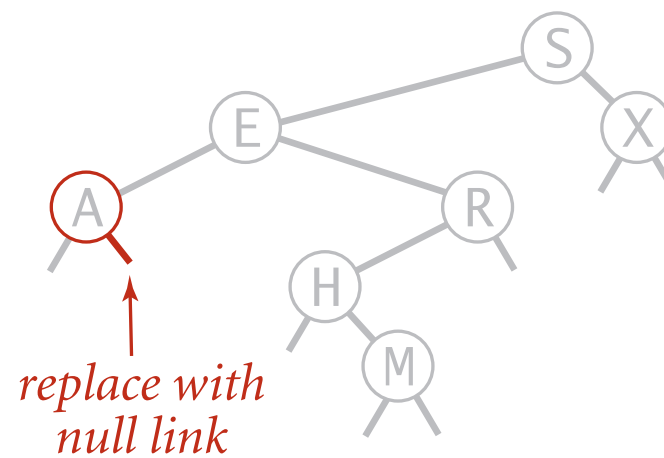
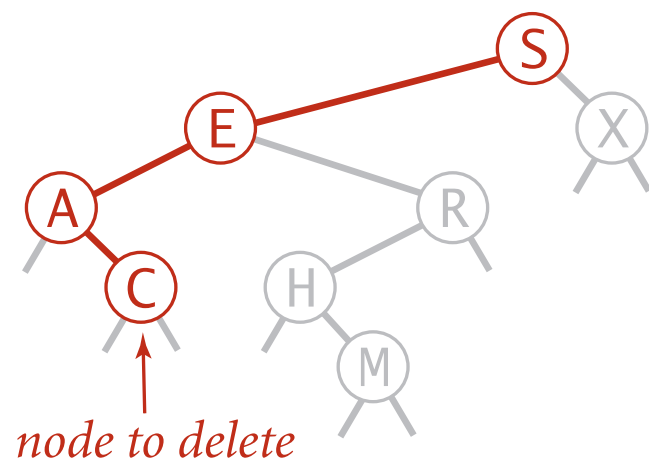
private Node deleteMin(Node x)
{
    if (x.left == null) return x.right;
    x.left = deleteMin(x.left);
    x.count = 1 + size(x.left) + size(x.right);
    return x;
}
```

Hibbard deletion

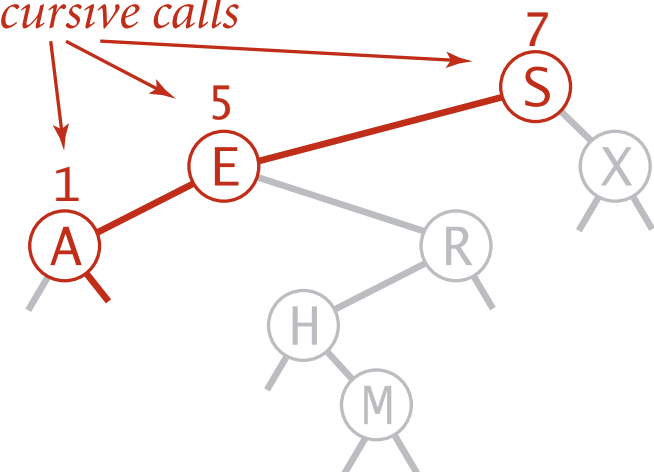
To delete a node with key k : search for node t containing key k .

Case 0. [0 children] Delete t by setting parent link to null.

deleting C



update counts after recursive calls

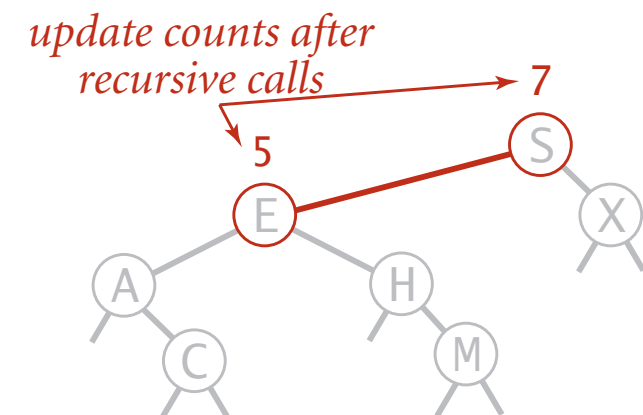
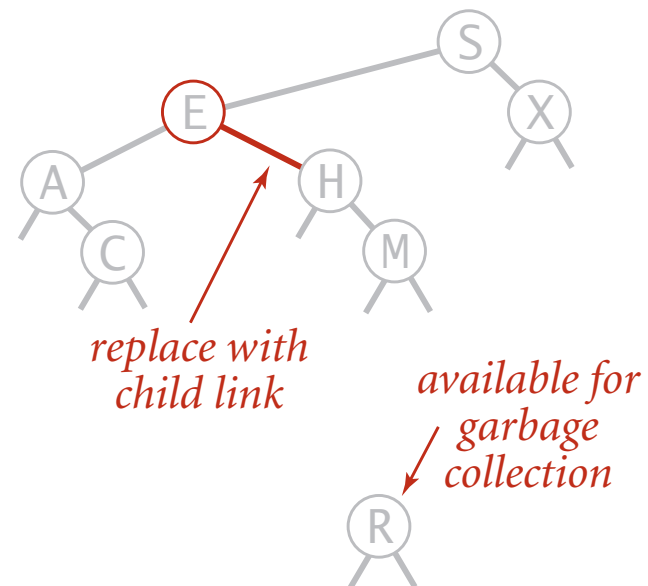
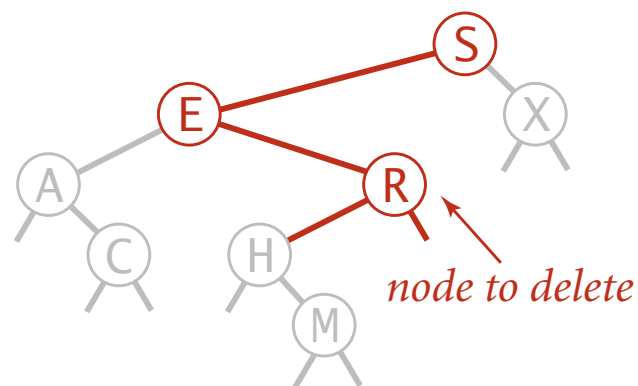


Hibbard deletion

To delete a node with key k : search for node t containing key k .

Case 1. [1 child] Delete t by replacing parent link.

deleting R



Hibbard deletion

To delete a node with key k : search for node t containing key k .

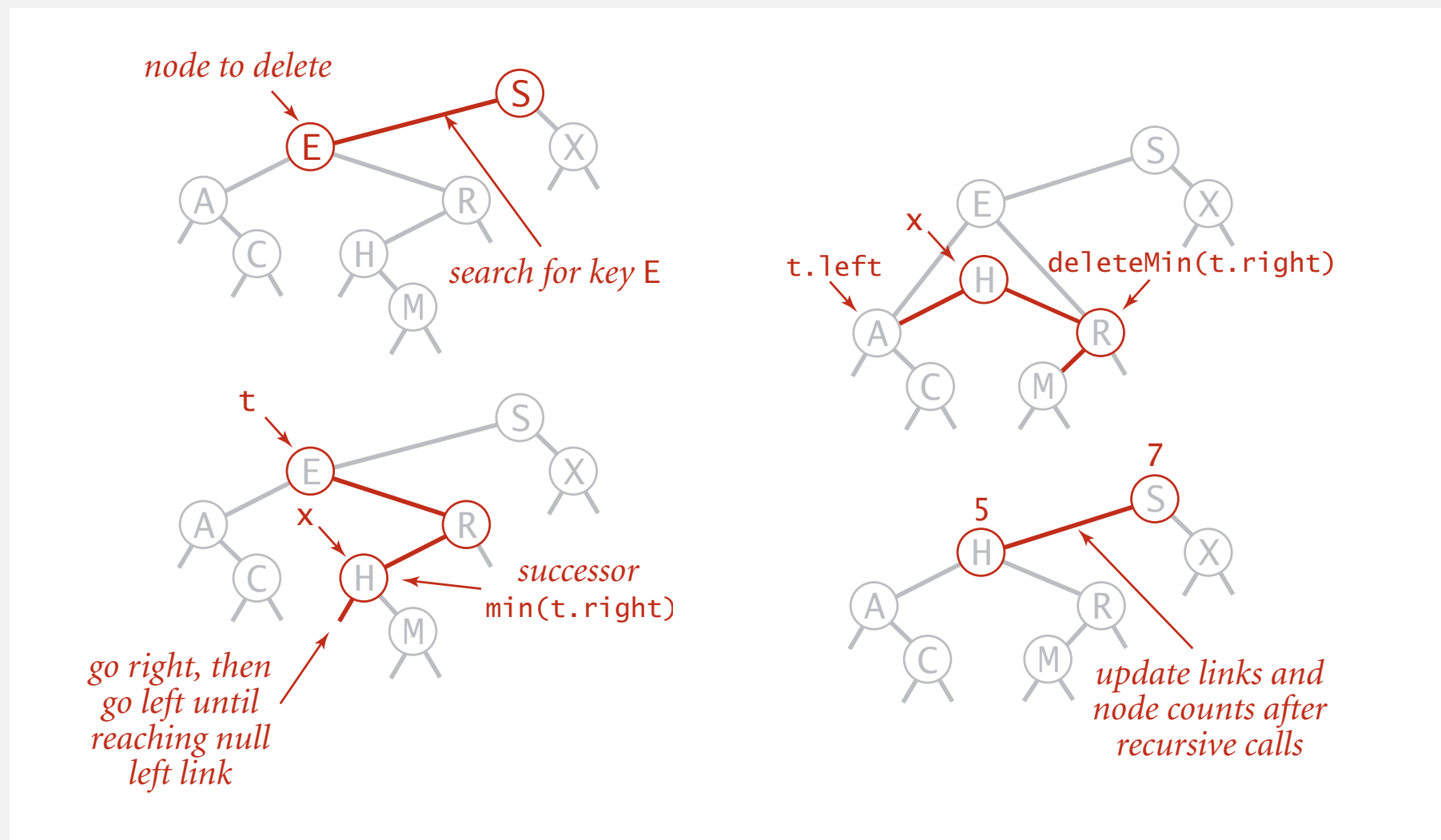
Case 2. [2 children]

- Find successor x of t .
- Delete the minimum in t 's right subtree.
- Put x in t 's spot.

← x has no left child

← but don't garbage collect x

← still a BST



Hibbard deletion: Java implementation

```
public void delete(Key key)
{ root = delete(root, key); }
```

```
private Node delete(Node x, Key key) {
```

```
    if (x == null) return null;
```

```
    int cmp = key.compareTo(x.key);
```

```
    if (cmp < 0) x.left = delete(x.left, key);
```

```
    else if (cmp > 0) x.right = delete(x.right, key);
```

```
    else {
```

```
        if (x.right == null) return x.left;
```

```
        if (x.left == null) return x.right;
```

```
        Node t = x;
```

```
        x = min(t.right);
```

```
        x.right = deleteMin(t.right);
```

```
        x.left = t.left;
```

```
    }
```

```
    x.count = size(x.left) + size(x.right) + 1;
```

```
    return x;
```

```
}
```

← search for key

← no right child

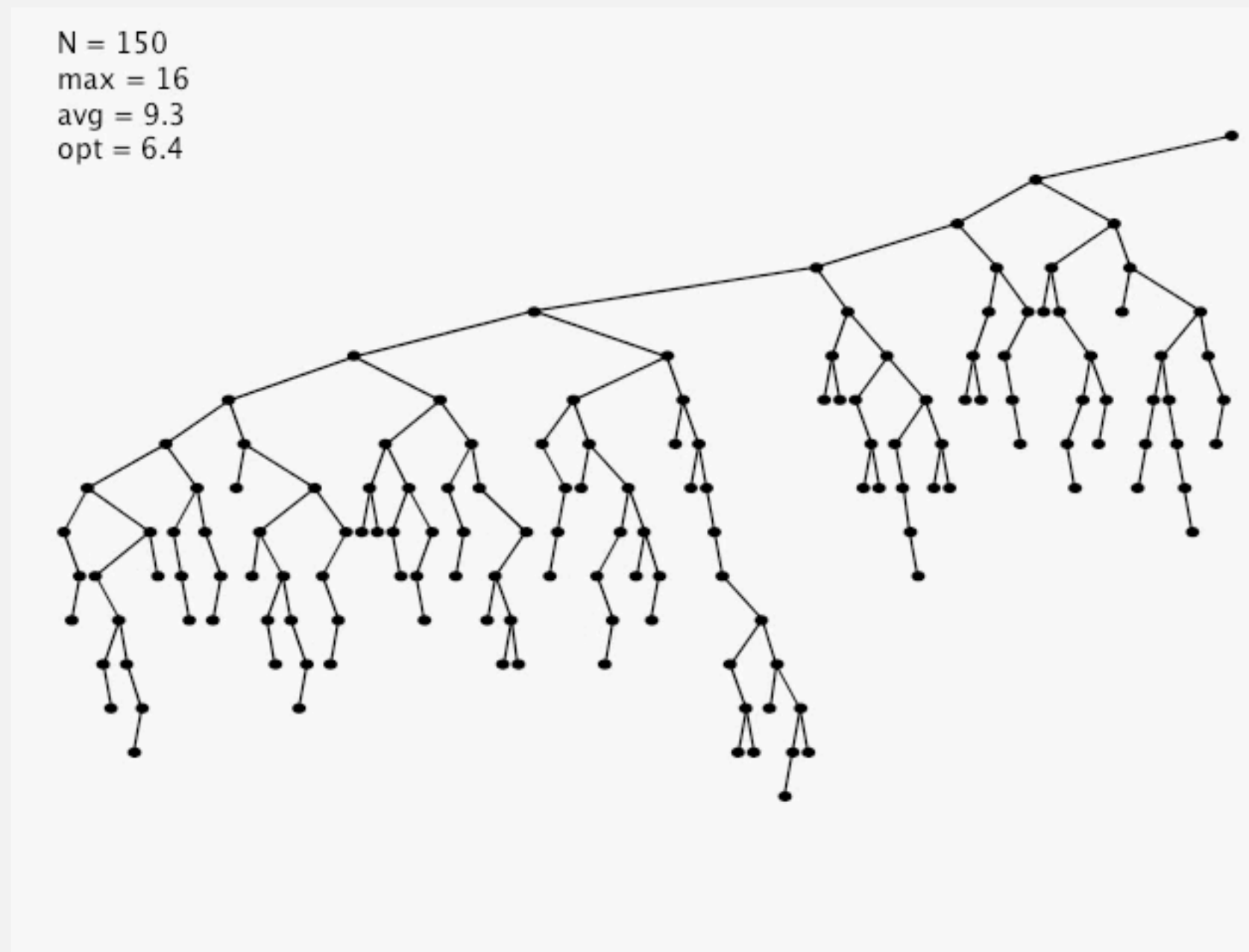
← no left child

← replace with
successor

← update subtree
counts

Hibbard deletion: analysis

Unsatisfactory solution. Not symmetric.



Surprising consequence. Trees not random (!) $\Rightarrow \sqrt{N}$ per op.

Longstanding open problem. Simple and efficient delete for BSTs.

ST implementations: summary

implementation	guarantee			average case			ordered ops?	operations on keys
	search	insert	delete	search hit	insert	delete		
sequential search (linked list)	N	N	N	$\frac{1}{2} N$	N	$\frac{1}{2} N$		equals()
binary search (ordered array)	$\lg N$	N	N	$\lg N$	$\frac{1}{2} N$	$\frac{1}{2} N$	✓	compareTo()
BST	N	N	N	$1.39 \lg N$	$1.39 \lg N$	\sqrt{N}	✓	compareTo()

other operations also become \sqrt{N}
if deletions allowed

Next lecture. **Guarantee** logarithmic performance for all operations.