BBM 202 - ALGORITHMS

HACETTEPE UNIVERSITY

DEPT. OF COMPUTER ENGINEERING

BINARY SEARCH TREES

Acknowledgement: The course slides are adapted from the slides prepared by R. Sedgewick
and K. Wayne of Princeton University.

TODAY

- BSTs
- Ordered operations
- Deletion

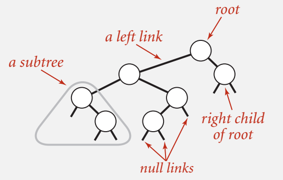
Binary Search Tree (BST)

- Last lecture, we talked about binary search & linear search
  - One had high cost for reorganisation,
  - The other had high cost for searching
- In this lecture we will use Binary Trees, for searching
- Plan in a nutshell:
  - Assert a more strict property compared to the Heap-Property (in priority-queues), Remember what that was?
  - Know exactly which subtree to look for at each node

Binary search trees

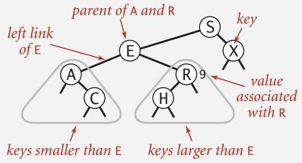
Definition. A BST is a binary tree in symmetric order.

A binary tree is either:
- Empty.
- Two disjoint binary trees (left and right).



Anatomy of a binary tree

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.



Anatomy of a binary search tree

BST representation in Java

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

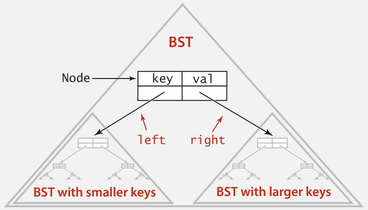
A `Node` is comprised of four fields:

- 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`



Binary search tree

BST implementation (skeleton)

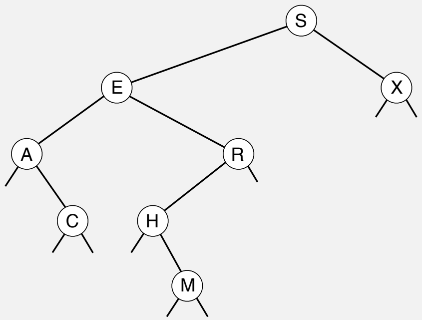
```
public class BST<Key extends Comparable<Key>, Value>
{
   private Node root;

   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 */  }

}
```

root of BST

Binary search tree operations

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

successful search for H



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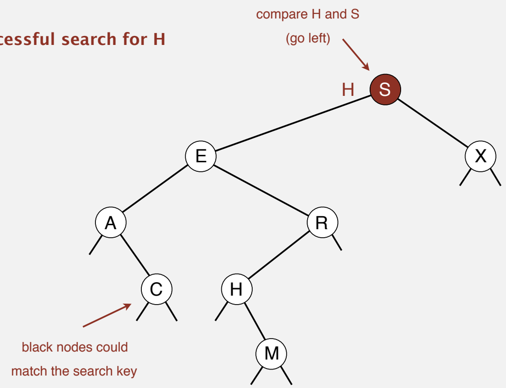

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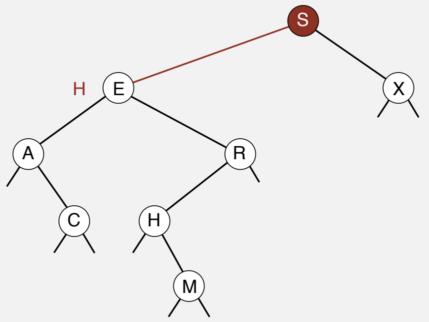

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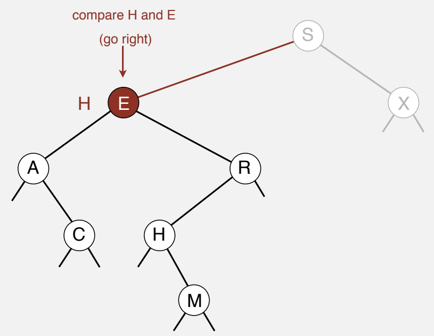

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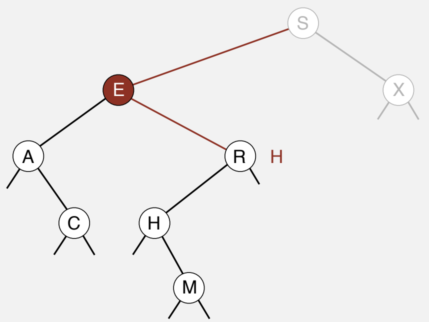

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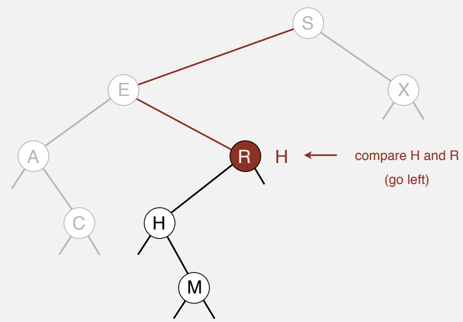

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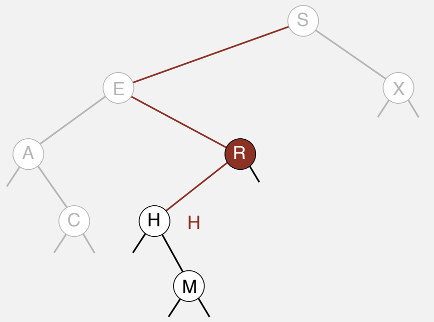

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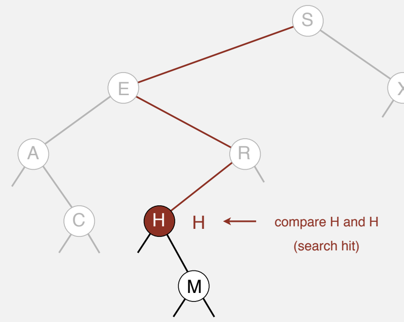
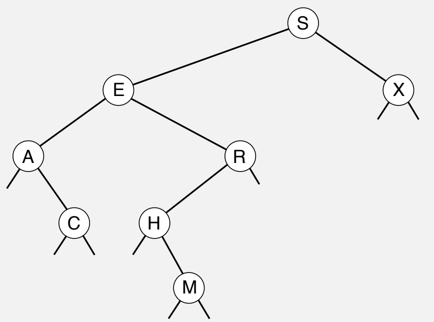


Binary search tree operations

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

unsuccessful search for G



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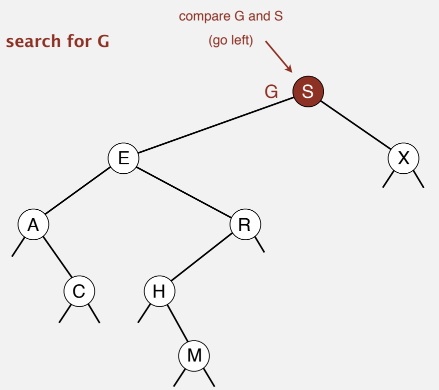

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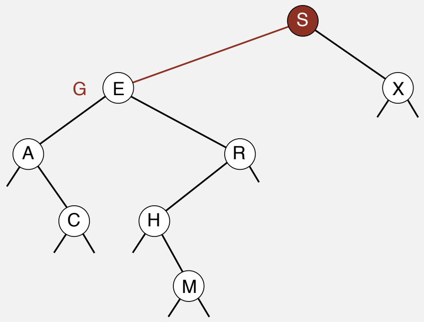

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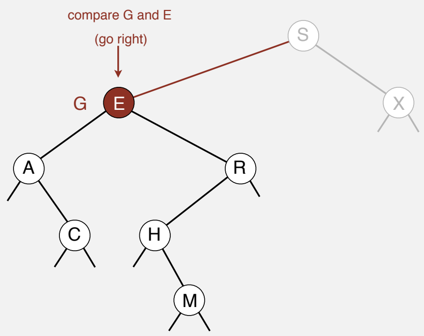

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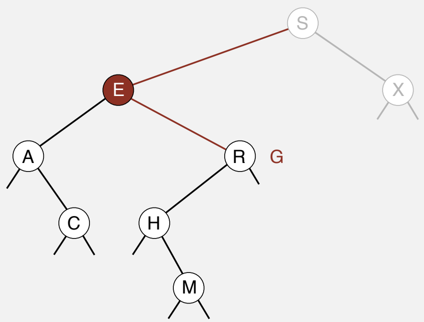

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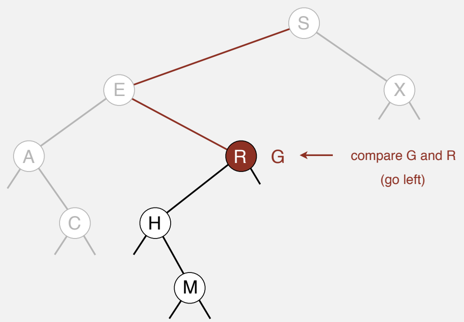

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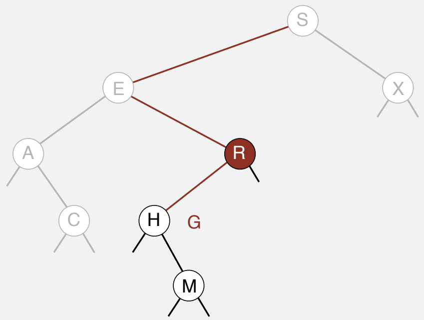

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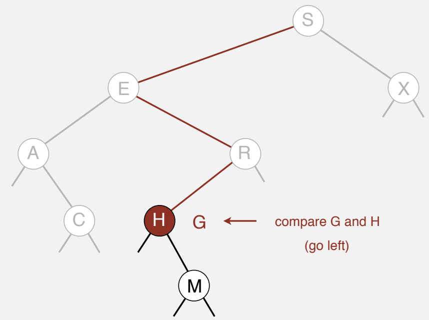

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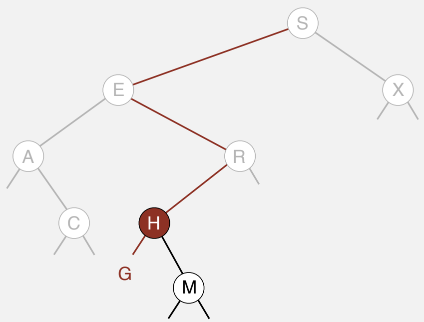

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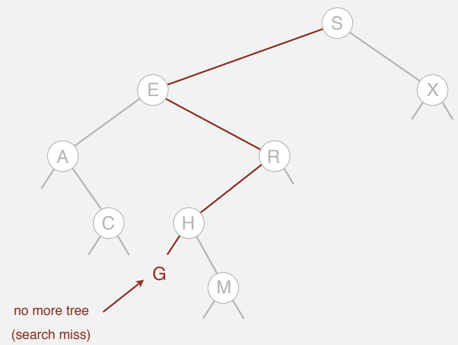
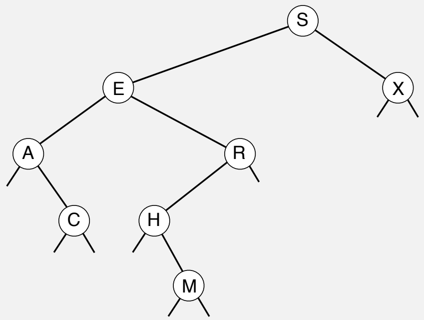


Binary search tree operations

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

insert G



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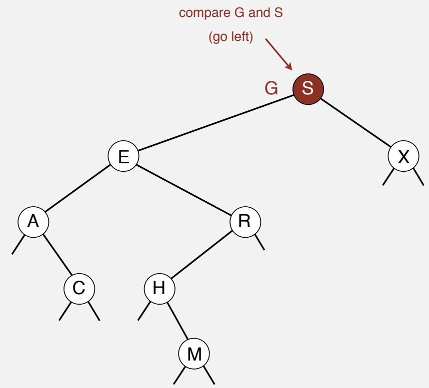

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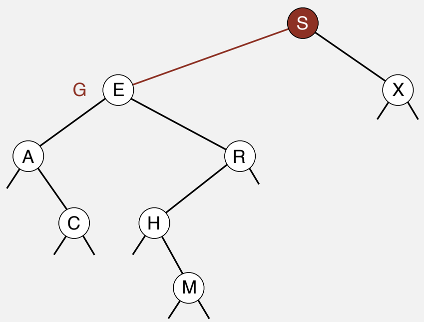

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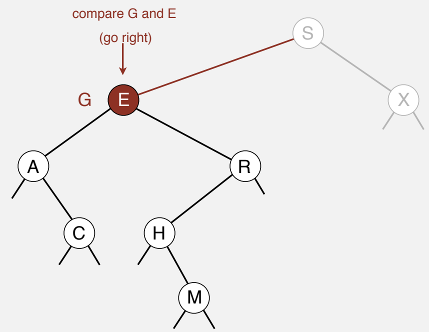

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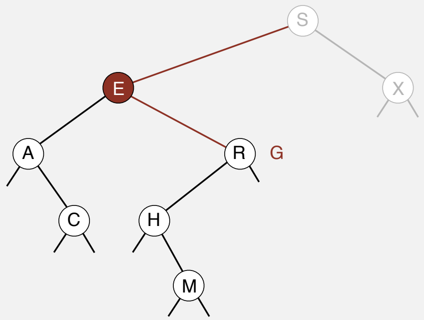

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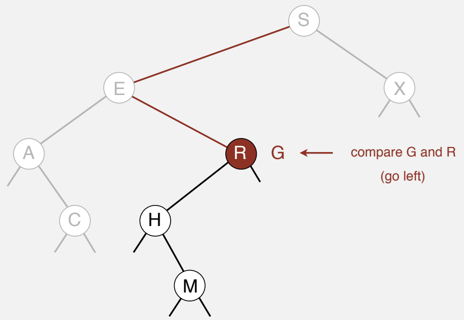

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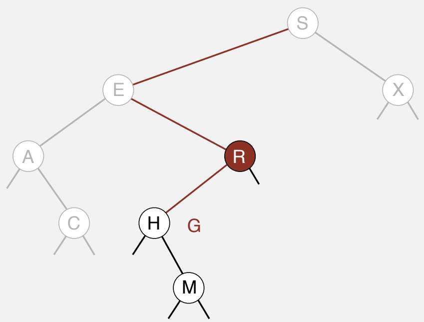

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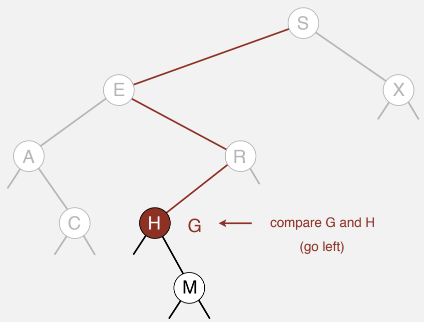

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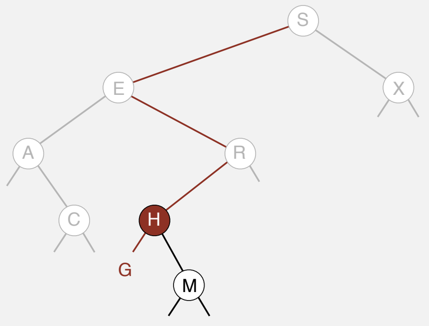

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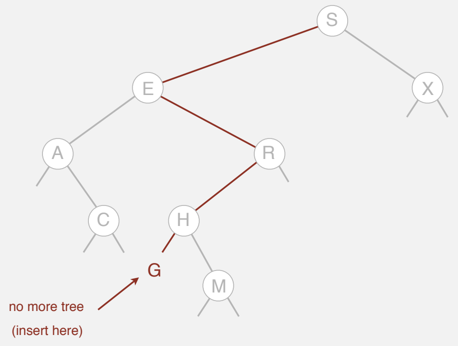

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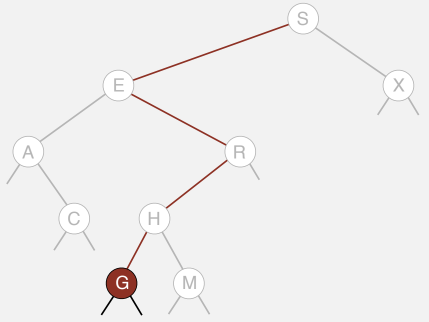

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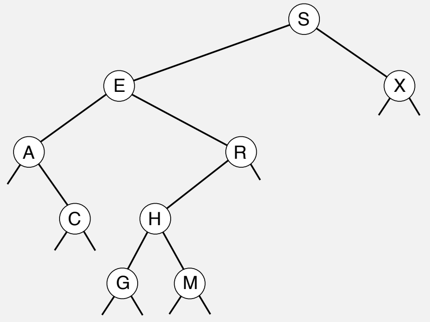
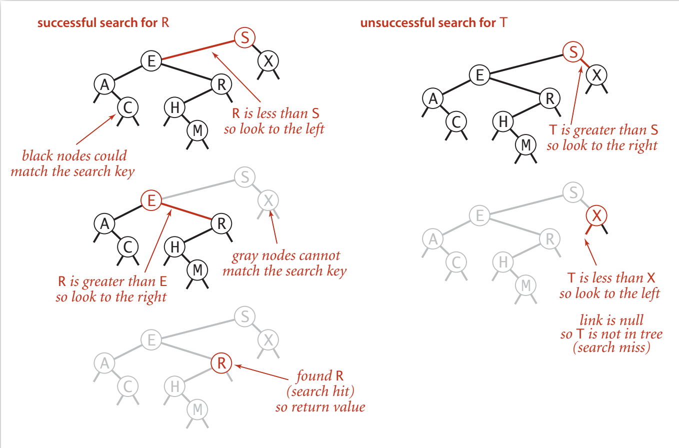


BST search

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



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;
}
```

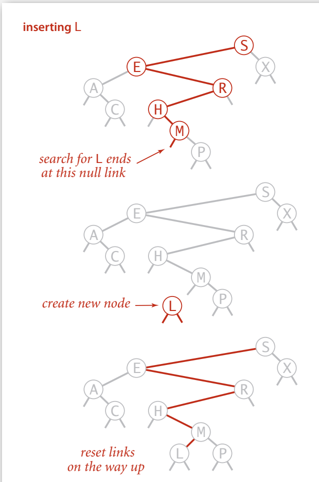
Cost. Number of compares is equal to 1 + depth of node.

BST insert

Put. Associate value with key.

Search for key, then two cases:

- Key in tree ⇒ reset value.
- Key not in tree ⇒ add new node.



Insertion into a BST

BST insert: Java implementation

Put. Associate value with key.

concise, but tricky, recursive code; read carefully!

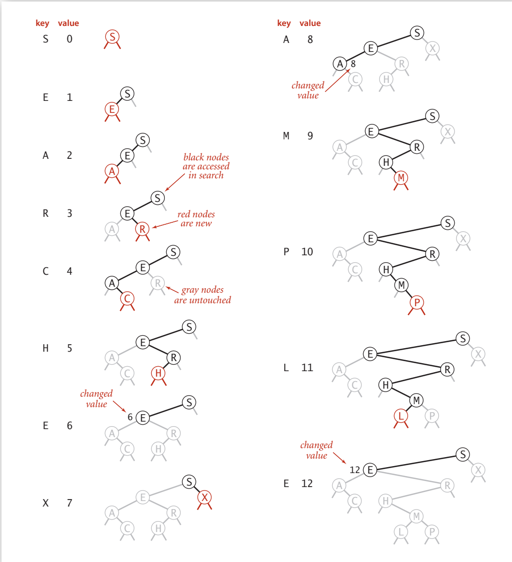
```
public void put(Key key, Value val)
{  root = put(root, key, val);  }

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;
}
```

Always assign the subtree returned from recursive call to a child, but does it actually change in each call ?

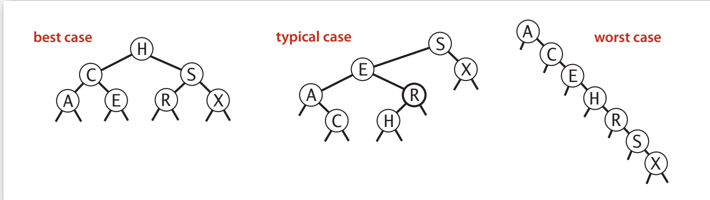
Cost. Number of compares is equal to 1 + depth of node.

BST trace: standard indexing client



Tree shape

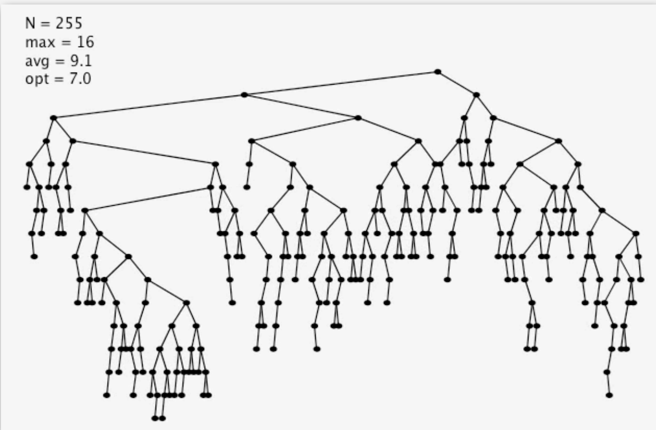
- Many BSTs correspond to same set of keys.
- Number of compares for search/insert is equal to 1 + depth of node.



Remark. Tree shape depends on order of insertion.

BST insertion: random order visualization

Ex. Insert keys in random order.



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
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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
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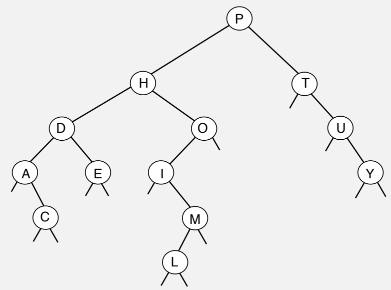


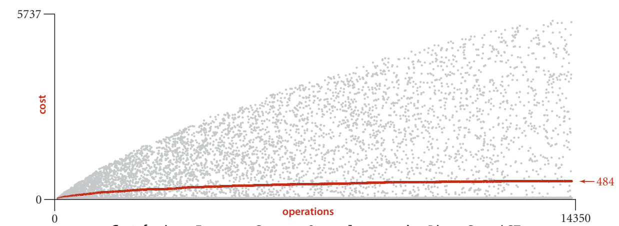
Remark. Correspondence is 1-1 if array has no duplicate keys.

BSTs: mathematical analysis

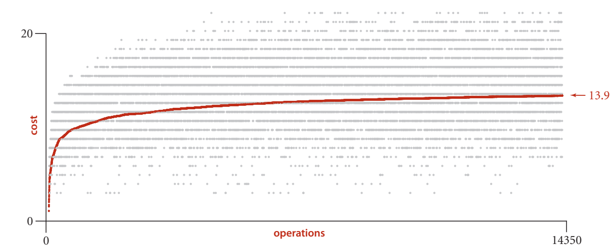
Proposition. If N distinct keys are inserted into a BST in random order, the expected number of compares for a search/insert is $O(\log N)$.
Pf. 1-1 correspondence with quicksort partitioning.

But… Worst-case height is N.
(exponentially small chance when keys are inserted in random order)

ST implementations: frequency counter



Costs for `java FrequencyCounter 8 < tale.txt` using `BinarySearchST`



Costs for `java FrequencyCounter 8 < tale.txt` using `BST`

ST implementations: summary

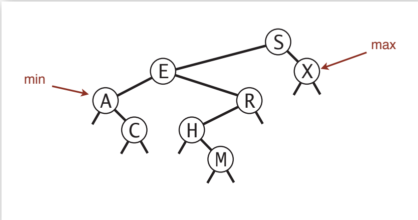
implementation	guarantee		average case		ordered ops?	operations on keys
	search	insert	search hit	insert		
sequential search (unordered list)	N	N	N/2	N	no	`equals()`
binary search (ordered array)	lg N	N	lg N	N/2	yes	`compareTo()`
BST	N	N	lg N	lg N	*stay tuned*	`compareTo()`

Binary Search Trees

- BSTs
- **Ordered operations**
- Deletion

Minimum and maximum

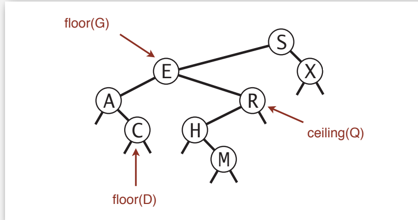
Minimum. Smallest key in table.
Maximum. Largest key in table.



Q. How to find the min / max?

Floor and ceiling

Floor. Largest key ≤ to a given key.
Ceiling. Smallest key ≥ to a given key.



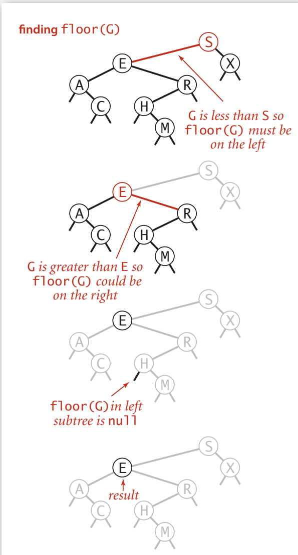
Q. How to find the floor /ceiling?

Computing the floor

Case 1. [k equals the key at root]
The floor of k is k.

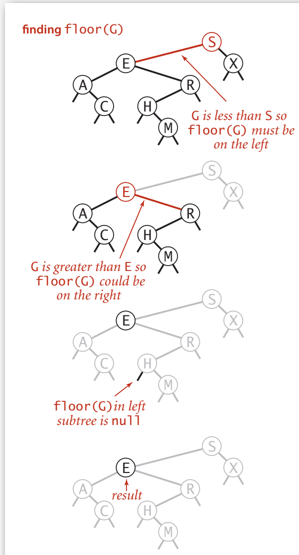
Case 2. [k is less than the key at root]
The floor of k is in the left subtree.

Case 3. [k is greater than the key at root]
The floor of k is in the right subtree
(if there is any key ≤ k in right subtree);
otherwise it is the key in the root.



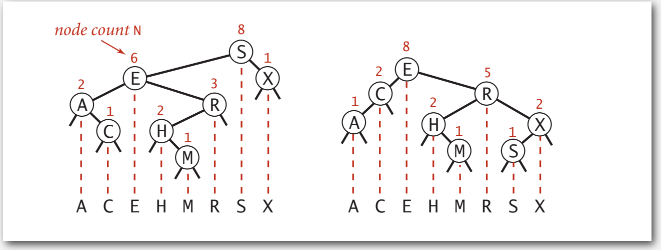
Computing the floor

```
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;

}
```



Subtree counts

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.



Remark. This facilitates efficient implementation of `rank()` and `select()`.

BST implementation: subtree counts

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

number of nodes in subtree

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

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

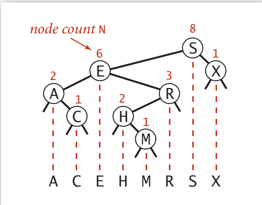
ok to call when x is null

```
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;
   x.N = 1 + size(x.left) + size(x.right);
   return x;
}
```


Rank

Rank. How many keys < k ?

Easy recursive algorithm (4 cases!)

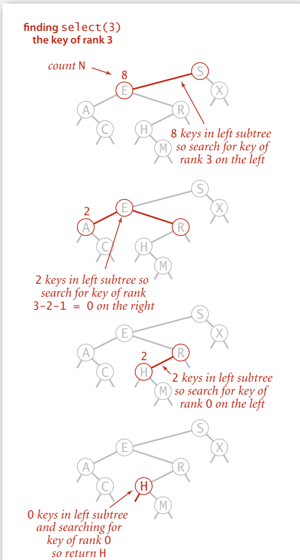



```
public int rank(Key key)
{  return rank(key, root);  }

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);
}
```


Selection

Select. Key of given rank.

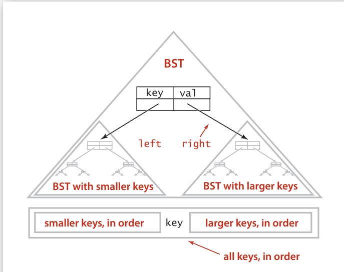
```
public Key select(int k)
{
   if (k < 0) return null;
   if (k >= size()) return null;
   Node x = select(root, k);
   return x.key;
}

private Node select(Node x, int k)
{
   if (x == null) return null;
   int t = size(x.left);
   if      (t  > k)
      return select(x.left,  k);
   else if (t  < k)
      return select(x.right, k-t-1);
   else if (t == k)
      return x;
}
```



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);
}
```

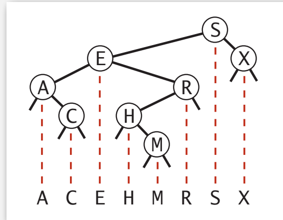


Property. Inorder traversal of a BST yields keys in ascending order.

Inorder traversal

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

recursive calls	queue	function call stack
inorder(S)		S
inorder(E)		S E
inorder(A)		S E A
enqueue A	A	
inorder(C)		S E A C
enqueue C	C	
enqueue E	E	
inorder(R)		S E R
inorder(H)		S E R H
enqueue H	H	
inorder(M)		S E R H M
enqueue M	M	
enqueue R	R	
enqueue S	S	
inorder(X)		S X
enqueue X	X	



BST: ordered symbol table operations summary

	sequential search	binary search	BST
search	N	lg N	h
insert	1	N	h
min / max	N	1	h
floor / ceiling	N	lg N	h
rank	N	lg N	h
select	N	1	h
ordered iteration	N log N	N	N

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

BINARY SEARCH TREES

- BSTs
- Ordered operations
- **Deletion**

ST implementations: summary

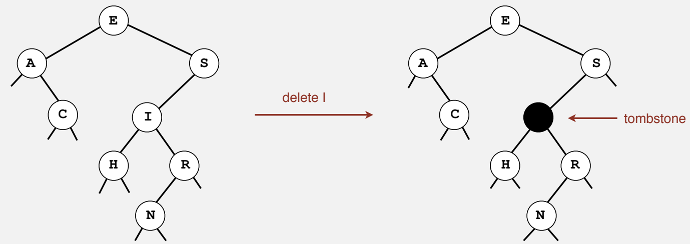
implementation	guarantee			average case			ordered iteration?	operations on keys
	search	insert	delete	search hit	insert	delete		
sequential search (linked list)	N	N	N	N/2	N	N/2	no	`equals()`
binary search (ordered array)	lg N	N	N	lg N	N/2	N/2	yes	`compareTo()`
BST	N	N	N	lg N	lg N	? ? ?	yes	`compareTo()`

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 searches (but don't consider it equal to search key).



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

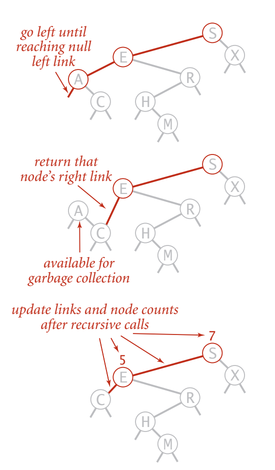
Unsatisfactory solution. Tombstone (memory) overload.

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.

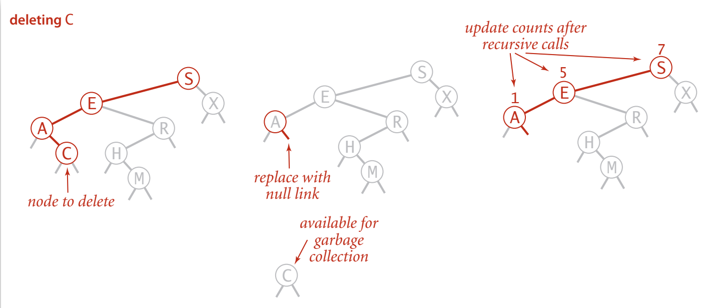
```
public void deleteMin()
{  root = deleteMin(root);  }

private Node deleteMin(Node x)
{
   if (x.left == null) return x.right;
   x.left = deleteMin(x.left);
   x.N = 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.

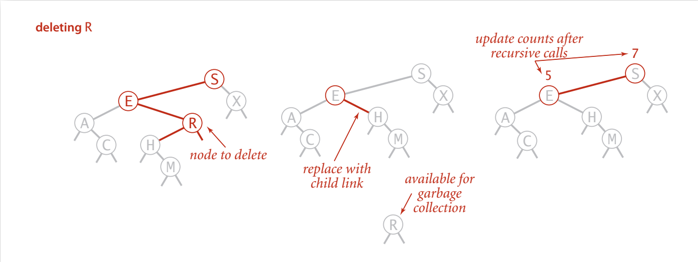
Case 0. [0 children] Delete t by setting parent link to null.



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.

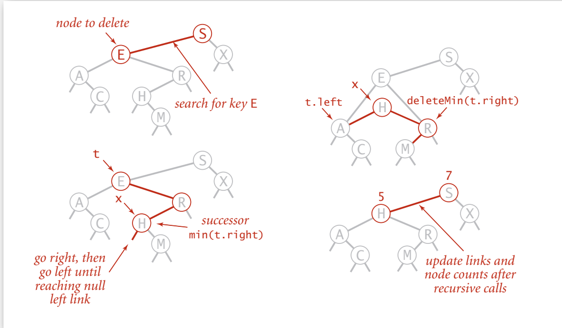


Hibbard deletion

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

Case 2. [2 children]

- Find successor x of t. ← x has no left child
- Delete the minimum in t's right subtree. ← but don't garbage collect x
- Put x in t's spot. ← 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;

      Node t = x;
      x = min(t.right);
      x.right = deleteMin(t.right);
      x.left = t.left;
   }
   x.N = size(x.left) + size(x.right) + 1;
   return x;
}
```

search for key

no right child

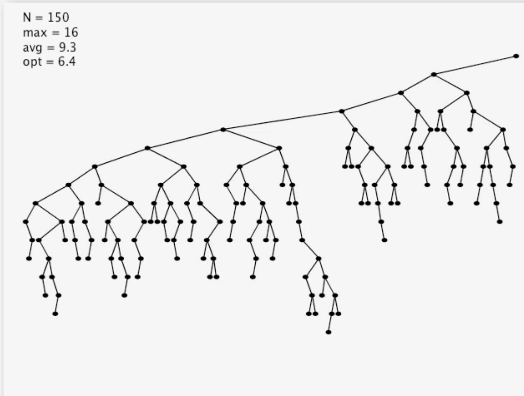
replace with successor

update subtree counts

Hibbard deletion: analysis

Unsatisfactory solution. Not symmetric.

If we always delete from the same side, the shape of tree will be not random, the right subtrees are trimmed!



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 iteration?	operations on keys
	search	insert	delete	search hit	insert	delete		
sequential search (linked list)	N	N	N	N/2	N	N/2	no	`equals()`
binary search (ordered array)	lg N	N	N	lg N	N/2	N/2	yes	`compareTo()`
BST	N	N	N	lg N	lg N	√N	yes	`compareTo()`

other operations also become √N
if deletions allowed

Red-black BST. Guarantee logarithmic performance for all operations.