

06-0: Ordered List ADT

Operations:

- Insert an element in the list
- Check if an element is in the list
- Remove an element from the list
- Print out the contents of the list, in order

06-1: Implementing Ordered List

Using an Ordered Array – Running times:

Check
Insert
Remove
Print

06-2: Implementing Ordered List

Using an Ordered Array – Running times:

Check $\Theta(\lg n)$
Insert $\Theta(n)$
Remove $\Theta(n)$
Print $\Theta(n)$

06-3: Implementing Ordered ListUsing an *Unordered* Array – Running times:

Check
Insert
Remove
Print

06-4: Implementing Ordered ListUsing an *Unordered* Array – Running times:

Check $\Theta(n)$
Insert $\Theta(1)$
Remove $\Theta(n)$ Need to find element first!
Print $\Theta(n \lg n)$
(Given a fast sorting algorithm)

06-5: Implementing Ordered List

Using an Ordered Linked List – Running times:

Check
Insert
Remove
Print

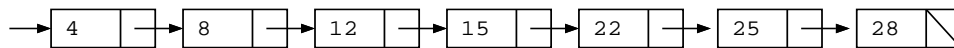
06-6: Implementing Ordered List

Using an Ordered Linked List – Running times:

- Check $\Theta(n)$
- Insert $\Theta(n)$
- Remove $\Theta(n)$
- Print $\Theta(n)$

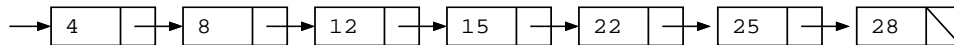
06-7: **The Best of Both Worlds**

- Linked Lists – Insert fast / Find slow
- Arrays – Find fast / Insert slow
- The only way to examine nth element in a linked list is to traverse (n-1) other elements

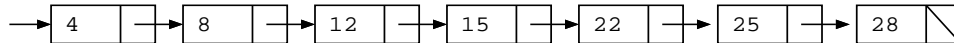


- If we could leap to the middle of the list ...

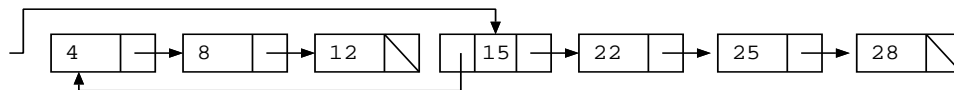
06-8: **The Best of Both Worlds**



06-9: **The Best of Both Worlds**

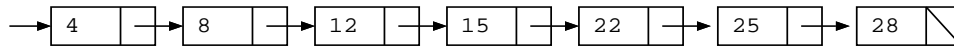


Move the initial pointer to the middle of the list:

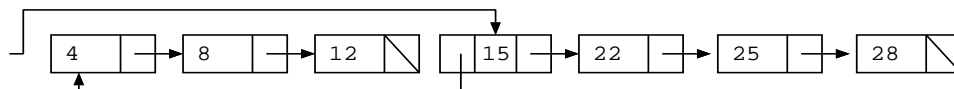


We've cut our search time in half! Have we changed the $\Theta()$ running time?

06-10: **The Best of Both Worlds**



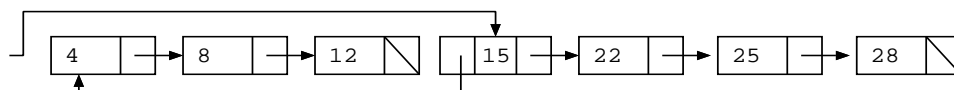
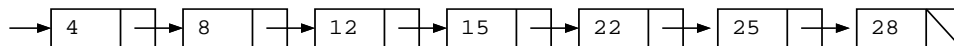
Move the initial pointer to the middle of the list:

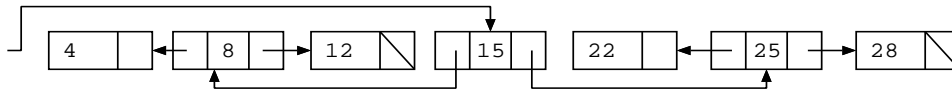


We've cut our search time in half! Have we changed the $\Theta()$ running time?

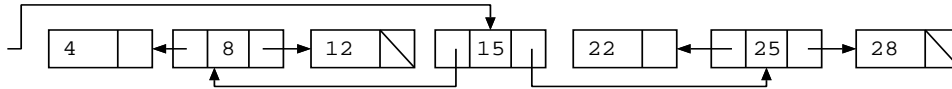
Repeat the process!

06-11: **The Best of Both Worlds**

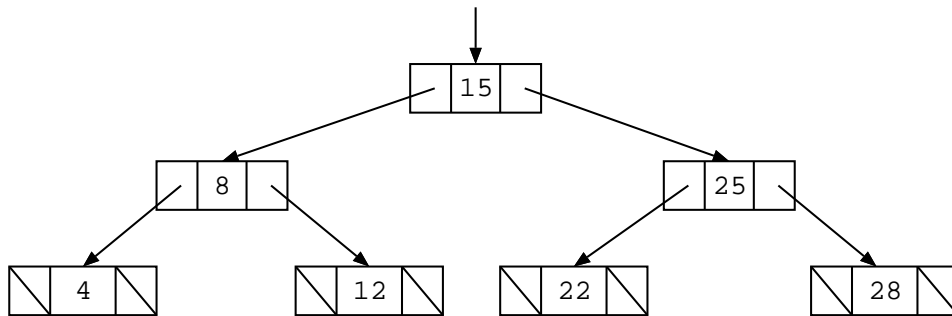




06-12: **The Best of Both Worlds** Grab the first element of the list:



Give it a good shake -



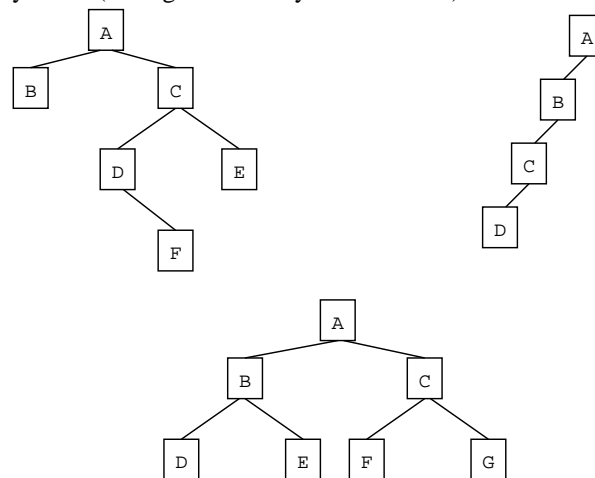
06-13: **Binary Trees**

Binary Trees are Recursive Data Structures

- Base Case: Empty Tree
- Recursive Case: Node, consisting of:
 - Left Child (Tree)
 - Right Child (Tree)
 - Data

06-14: **Binary Tree Examples**

The following are all Binary Trees (Though not Binary Search Trees)



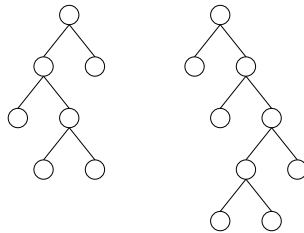
06-15: **Tree Terminology**

- Parent / Child

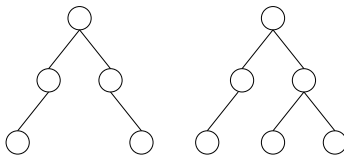
- Leaf node
- Root node
- Edge (between nodes)
- Path
- Ancestor / Descendant
- Depth of a node n
 - Length of path from root to n
- Height of a tree
 - (Depth of deepest node) + 1

06-16: **Full Binary Tree**

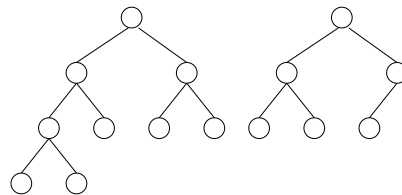
- Each node has 0 or 2 children
- Full Binary Trees



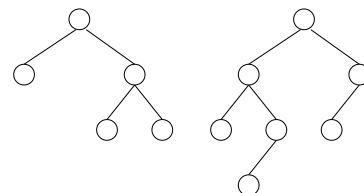
- *Not* Full Binary Trees

06-17: **Complete Binary Tree**

- Can be built by starting at the root, and filling the tree by levels from left to right



- Complete Binary Trees

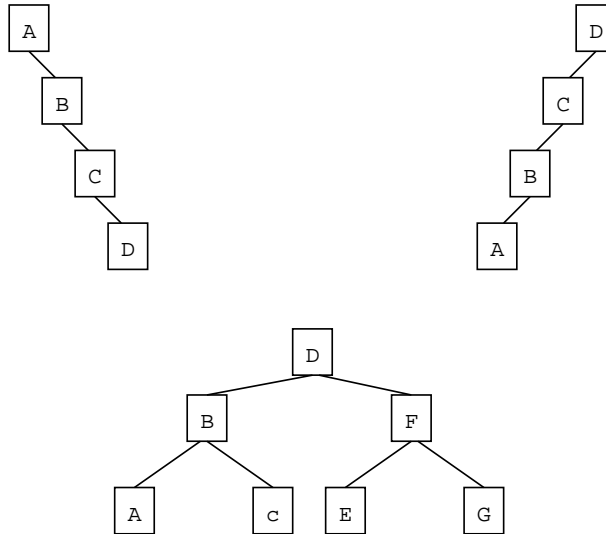


- *Not* Complete Binary Trees

06-18: Binary Search Trees

- Binary Trees
- For each node n , (value stored at node n) \geq (value stored in left subtree)
- For each node n , (value stored at node n) $<$ (value stored in right subtree)

06-19: Example Binary Search Trees



06-20: Implementing BSTs

- Each Node in a BST is implemented as a class:

```

public class Node {
    public Comparable data;
    public Node left;
    public Node right;
}
  
```

06-21: Implementing BSTs

```

public class Node {
    public Node(Comparable data, Node left, Node right) {
        this.data = data;
        this.left = left;
        this.right = right;
    }

    public Node left() {
        return left;
    }
    public Node setLeft(Node newLeft) {
        left = newLeft;
    }
    ... (etc)

    private Comparable data;
    private Node left;
    private Node right;
}
  
```

06-22: Finding an Element in a BST

- Binary Search Trees are recursive data structures, so most operations on them will be recursive as well

- Recall how to write a recursive algorithm ...

06-23: Writing a Recursive Algorithm

- Determine a small version of the problem, which can be solved immediately. This is the *base case*
- Determine how to make the problem smaller
- Once the problem has been made smaller, we can assume that the function that we are writing *will work correctly on the smaller problem* (Recursive Leap of Faith)
 - Determine how to use the solution to the smaller problem to solve the larger problem

06-24: Finding an Element in a BST

- First, the Base Case – when is it easy to determine if an element is stored in a Binary Search Tree?

06-25: Finding an Element in a BST

- First, the Base Case – when is it easy to determine if an element is stored in a Binary Search Tree?
 - If the tree is empty, then the element can't be there
 - If the element is stored at the root, then the element is there

06-26: Finding an Element in a BST

- Next, the Recursive Case – how do we make the problem smaller?

06-27: Finding an Element in a BST

- Next, the Recursive Case – how do we make the problem smaller?
 - Both the left and right subtrees are smaller versions of the problem. Which one do we use?

06-28: Finding an Element in a BST

- Next, the Recursive Case – how do we make the problem smaller?
 - Both the left and right subtrees are smaller versions of the problem. Which one do we use?
 - If the element we are trying to find is $<$ the element stored at the root, use the left subtree. Otherwise, use the right subtree.

06-29: Finding an Element in a BST

- Next, the Recursive Case – how do we make the problem smaller?
 - Both the left and right subtrees are smaller versions of the problem. Which one do we use?
 - If the element we are trying to find is $<$ the element stored at the root, use the left subtree. Otherwise, use the right subtree.
- How do we use the solution to the subproblem to solve the original problem?

06-30: Finding an Element in a BST

- Next, the Recursive Case – how do we make the problem smaller?

- Both the left and right subtrees are smaller versions of the problem. Which one do we use?
- If the element we are trying to find is $<$ the element stored at the root, use the left subtree. Otherwise, use the right subtree.
- How do we use the solution to the subproblem to solve the original problem?
 - The solution to the subproblem *is* the solution to the original problem (this is not always the case in recursive algorithms)

06-31: Finding an Element in a BST

To find an element e in a Binary Search Tree T :

- If T is empty, then e is not in T
- If the root of T contains e , then e is in T
- If $e <$ the element stored in the root of T :
 - Look for e in the left subtree of T

Otherwise

- Look for e in the right subtree of T

06-32: Finding an Element in a BST

```
boolean find(Node tree, Comparable elem) {
    if (tree == null)
        return false;
    if (elem.compareTo(tree.element()) == 0)
        return true;
    if (elem.compareTo(tree) < 0)
        return find(tree.left(), elem);
    else
        return find(tree.right(), elem);
}
```

06-33: Printing out a BST

To print out all element in a BST:

- Print all elements in the left subtree, in order
- Print out the element at the root of the tree
- Print all elements in the right subtree, in order

06-34: Printing out a BST

To print out all element in a BST:

- Print all elements in the left subtree, in order
- Print out the element at the root of the tree
- Print all elements in the right subtree, in order

- Each subproblem is a smaller version of the original problem – we can assume that a recursive call will work!

06-35: Printing out a BST

- What is the base case for printing out a Binary Search Tree – what is an easy tree to print out?

06-36: Printing out a BST

- What is the base case for printing out a Binary Search Tree – what is an easy tree to print out?
- An empty tree is extremely easy to print out – do nothing!
- Code for printing a BST ...

06-37: Printing out a BST

```
void print(Node tree) {  
    if (tree != null) {  
        print(tree.left());  
        System.out.println(tree.element());  
        print(tree.right());  
    }  
}
```

06-38: Printing out a BST

Examples

06-39: Tree Traversals

- PREORDER Traversal
 - Do operation on root of the tree
 - Traverse left subtree
 - Traverse right subtree
- INORDER Traversal
 - Traverse left subtree
 - Do operation on root of the tree
 - Traverse right subtree
- POSTORDER Traversal
 - Traverse left subtree
 - Traverse right subtree
 - Do operation on root of the tree

06-40: PREORDER Examples**06-41: POSTORDER Examples****06-42: INORDER Examples****06-43: BST Minimal Element**

To find the minimal element in a BST:

- Base Case: When is it easy to find the smallest element in a BST?
- Recursive Case: How can we make the problem smaller?

How can we use the solution to the smaller problem to solve the original problem?

06-44: **BST Minimal Element**

To find the minimal element in a BST:

Base Case:

- When is it easy to find the smallest element in a BST?

06-45: **BST Minimal Element**

To find the minimal element in a BST:

Base Case:

- When is it easy to find the smallest element in a BST?
 - When the left subtree is empty, then the element stored at the root is the smallest element in the tree.

06-46: **BST Minimal Element**

To find the minimal element in a BST:

Recursive Case:

- How can we make the problem smaller?

06-47: **BST Minimal Element**

To find the minimal element in a BST:

Recursive Case:

- How can we make the problem smaller?
 - Both the left and right subtrees are smaller versions of the same problem
- How can we use the solution to a smaller problem to solve the original problem?

06-48: **BST Minimal Element**

To find the minimal element in a BST:

Recursive Case:

- How can we make the problem smaller?
 - Both the left and right subtrees are smaller versions of the same problem
- How can we use the solution to a smaller problem to solve the original problem?
 - The smallest element in the left subtree is the smallest element in the tree

06-49: **BST Minimal Element**

```
Comparable minimum(Node tree) {
    if (tree == null)
        return null;
    if (tree.left() == null)
        return tree.element();
    else
        return minimum(tree.left());
}
```

06-50: BST Minimal Element

Iterative Version

```
Comparable minimum(Node tree) {
    if (tree == null)
        return null;
    while (tree.left() != null)
        tree = tree.left();
    return tree.element();
}
```

06-51: Inserting e into BST T

- What is the base case – an easy tree to insert an element into?

06-52: Inserting e into BST T

- What is the base case – an easy tree to insert an element into?
 - An empty tree
 - Create a new tree, containing the element e

06-53: Inserting e into BST T

- Recursive Case: How do we make the problem smaller?

06-54: Inserting e into BST T

- Recursive Case: How do we make the problem smaller?
 - The left and right subtrees are smaller versions of the same problem.
 - How do we use these smaller versions of the problem?

06-55: Inserting e into BST T

- Recursive Case: How do we make the problem smaller?
 - The left and right subtrees are smaller versions of the same problem
 - Insert the element into the left subtree if $e \leq$ value stored at the root, and insert the element into the right subtree if $e >$ value stored at the root

06-56: Inserting e into BST T

- Base case – T is empty:
 - Create a new tree, containing the element e
- Recursive Case:
 - If e is less than the element at the root of T , insert e into left subtree
 - If e is greater than the element at the root of T , insert e into the right subtree

06-57: Tree Manipulation in Java

- Tree manipulation functions return trees
- Insert method takes as input the old tree and the element to insert, and returns the new tree, with the element inserted
 - Old value (pre-insertion) of tree will be destroyed
- To insert an element e into a tree T :
 - $T = \text{insert}(T, e);$

06-58: Inserting e into BST T

```
Node insert(Node tree, Comparable elem) {
    if (tree == null) {
        return new Node(elem);
    }
    if (elem.compareTo(tree.element() <= 0)) {
        tree.setLeft(insert(tree.left(), elem));
        return tree;
    } else {
        tree.setRight(insert(tree.right(), elem));
        return tree;
    }
}
```

06-59: Deleting From a BST

- Removing a leaf:

06-60: Deleting From a BST

- Removing a leaf:
 - Remove element immediately

06-61: Deleting From a BST

- Removing a leaf:
 - Remove element immediately
- Removing a node with one child:

06-62: Deleting From a BST

- Removing a leaf:
 - Remove element immediately
- Removing a node with one child:
 - Just like removing from a linked list
 - Make parent point to child

06-63: Deleting From a BST

- Removing a leaf:
 - Remove element immediately
- Removing a node with one child:
 - Just like removing from a linked list
 - Make parent point to child
- Removing a node with two children:

06-64: Deleting From a BST

- Removing a leaf:
 - Remove element immediately
- Removing a node with one child:
 - Just like removing from a linked list
 - Make parent point to child
- Removing a node with two children:
 - Replace node with largest element in left subtree, or the smallest element in the right subtree

06-65: Comparable vs. .key() method

- We have been storing “Comparable” elements in BSTs
- Alternately, could use a “key()” method – elements stored in BSTs must implement a key() method, which returns an integer.
- We can combine the two methods
 - Each element stored in the tree has a key() method
 - key() method returns Comparable class

06-66: BST Implementation Details

- Use BSTs to implement Ordered List ADT
- Operations
 - Insert
 - Find
 - Remove
 - Print in Order
- The specification (interface) should not specify an implementation
 - Allow several different implementations of the same interface

06-67: BST Implementation Details

- BST functions require the root of the tree be sent in as a parameter

- Ordered list functions should *not* contain implementation details!
- What should we do?

06-68: **BST Implementation Details**

- BST functions require the root of the tree be sent in as a parameter
- Ordered list functions should *not* contain implementation details!
- What should we do?
 - Private variable, holds root of the tree
 - Private recursive methods, require root as an argument
 - Public methods call private methods, passing in private root