

Balanced Trees

- in an ideal world we would like to always ensure that our binary trees are perfectly balanced
- keeping a tree perfectly balanced after each deletion and insertion is computationally expensive

AVL Trees

- Adelson-Velskii and Landis postulated a more relaxed definition for balancing a tree
 - a tree is balanced if and only if for every node the heights of its two subtrees differ by at most 1
- this provides a compromise between efficient tree access and the need to rebalance

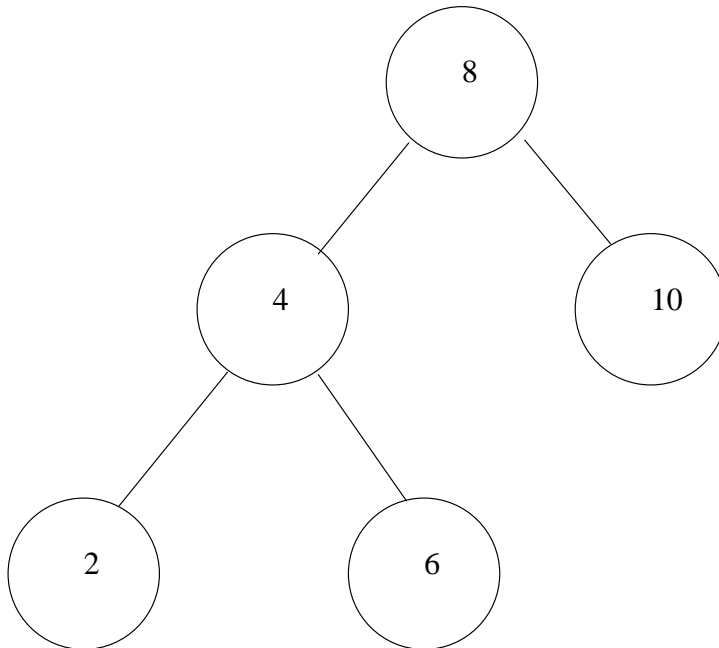
AVL Trees

- consider insertion of a new `int` on the `left` branch, causing the `left` height to increase by one

- here we have three cases
 - `height(left) == height(right)`: `left` and `right` become of unequal height, but the balance criterion is not violated
 - `height(left) < height(right)`: `left` and `right` become of equal height, balance criterion was improved
 - `height(left) > height(right)`: `left` and `right` differ by 2, balance criterion was violated, the tree must be balanced

AVL Trees

- consider adding 1, 3, 5, 7, 9 and 11



- which numbers require the tree to be rebalanced?

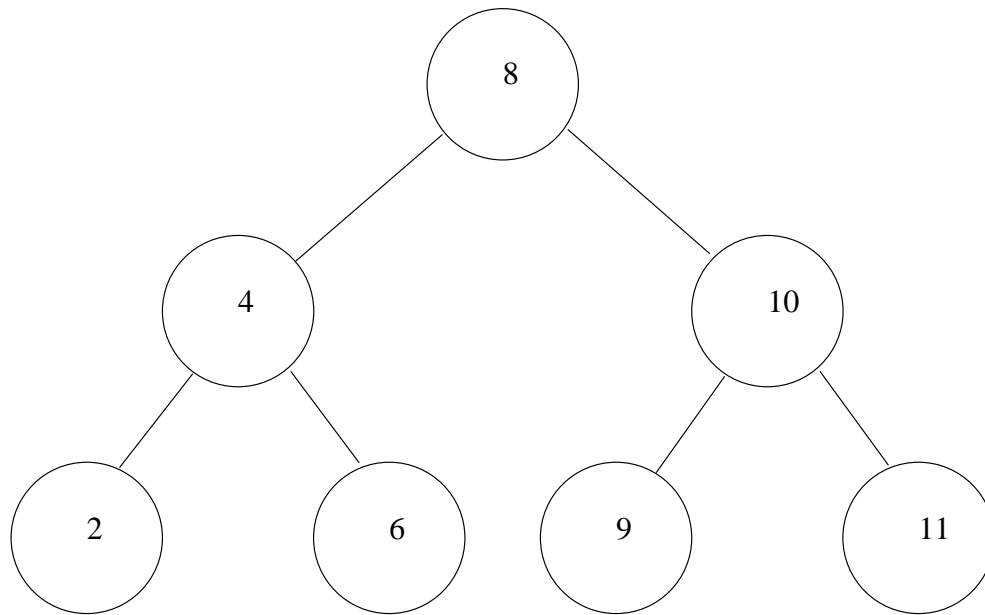
AVL Trees

- in summary we need to rebalance the tree if the left and right height differ by two or more

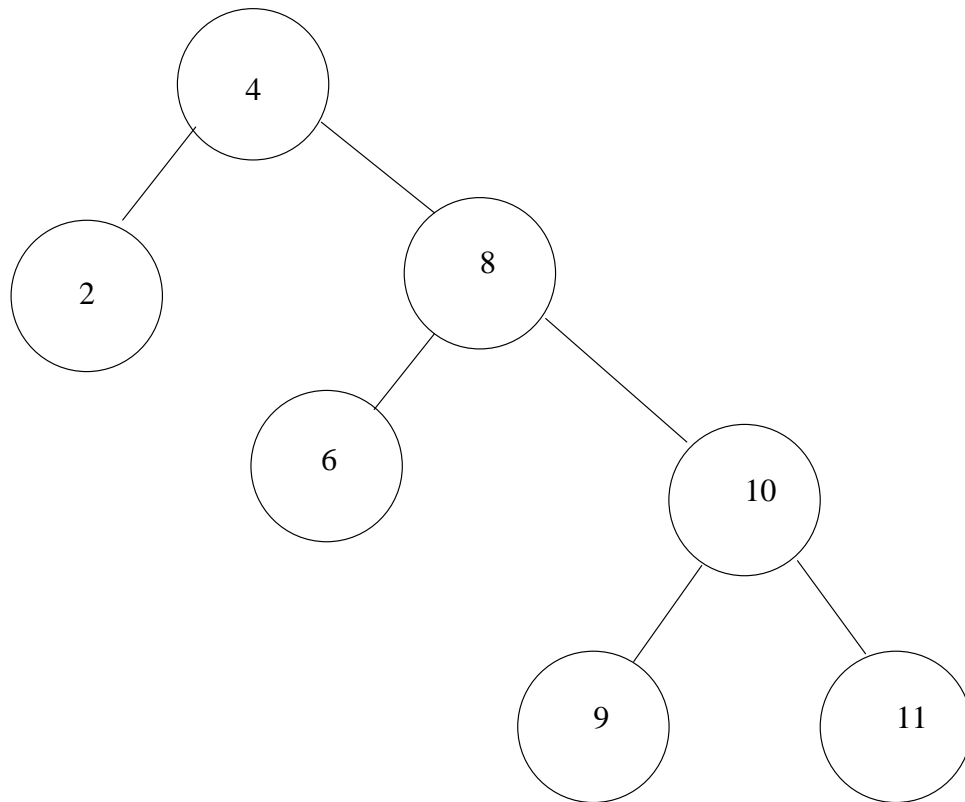
Rebalancing a tree

- rebalancing a tree is achieved through two operations which might be applied a number of times
 - rotate right
 - rotate left

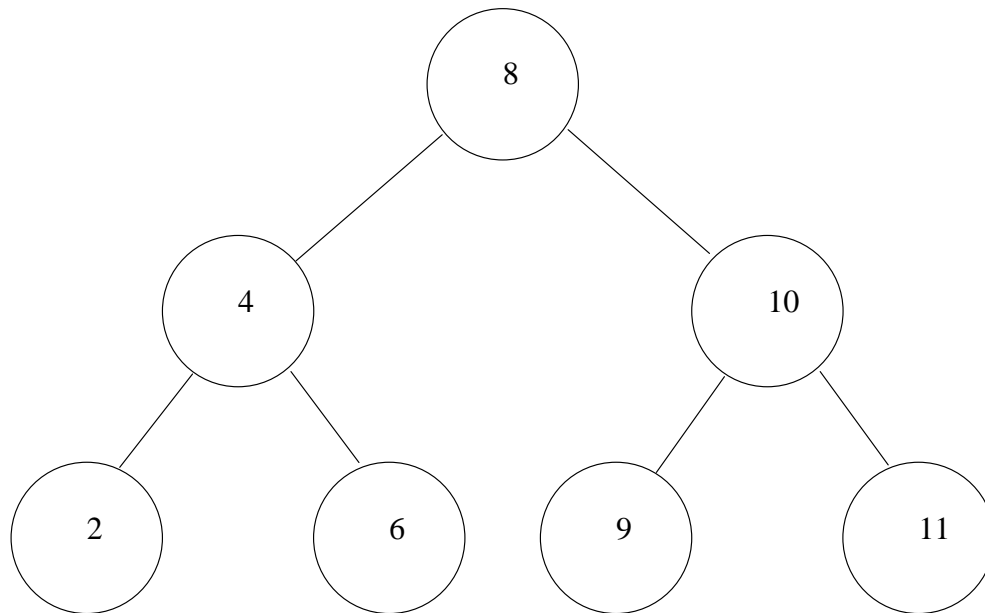
Rotate right



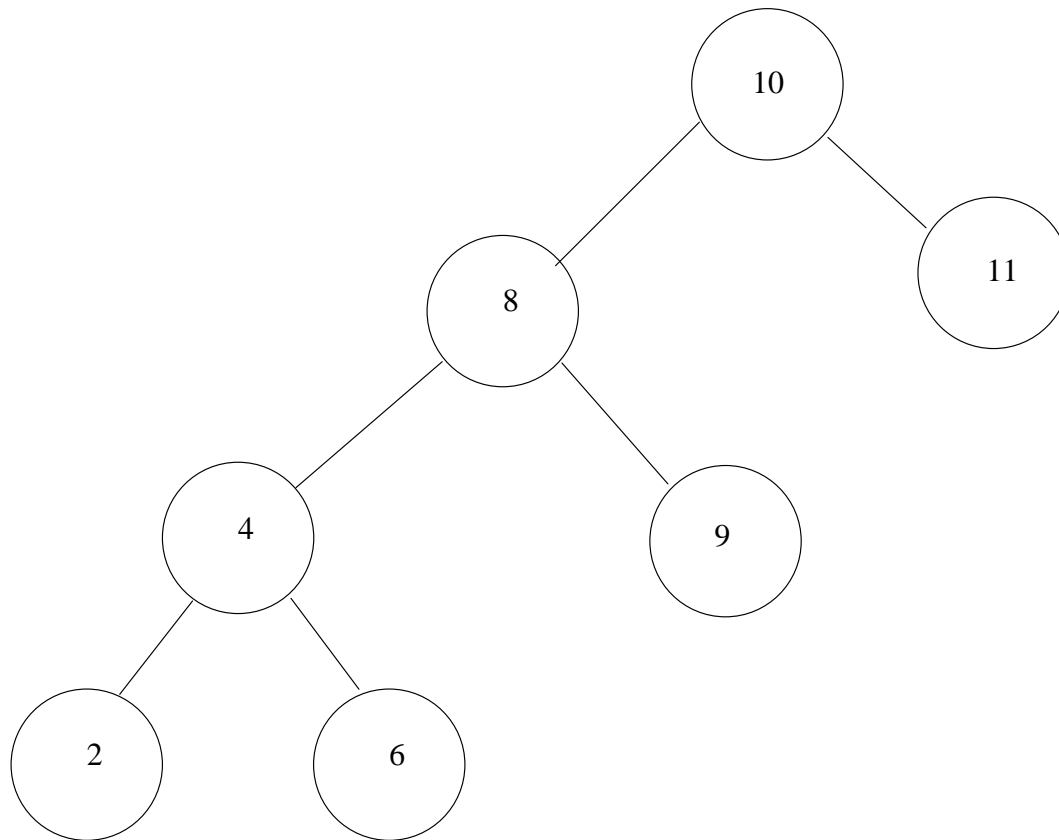
Rotate right



Rotate left



Rotate left



Rotate left axioms

■

```
rotate_left (empty ())      -> empty ()
rotate_left (cons (i, l, r) -> cons (root (r),
                                     cons (i, l, left (r)),
                                     right (r))
```

rotate_right

examples/c++/trees/avl/int/tree.cc

```
/*  
 * rotate_right - pre-condition : left branch is not empty.  
 *                post-condition: a new tree is return which  
 *                is the result of rotating the  
 *                current tree.  
 */  
  
tree tree::rotate_right (void)  
{  
    if (is_empty ())  
        return *this;  
    else  
        return cons (left ().root (),  
                    left ().left (),  
                    cons (root (),  
                        left ().right (),  
                        right ()));  
}
```

rotate_left

examples/c++/trees/avl/int/tree.cc

```
/*
 * rotate_left - pre-condition : right branch is not empty.
 *               post-condition: a new tree is return which
 *               is the result of rotating the
 *               current tree.
 */

tree tree::rotate_left (void)
{
    if (is_empty ())
        return *this;
    else
        return cons (right ().root (),
                    cons (root (),
                        left (),
                        right ().left ()),
                    right ().right ());
}
```

insert

■ [examples/c++/trees/avl/int/tree.cc](#)

```
tree tree::insert (int i)
{
    if (is_empty ())
        return cons (i, empty (), empty ());
    else
        return insert_non_empty (i).balance ();
}
```

balance

examples/c++/trees/avl/int/tree.cc

```
tree tree::balance (void)
{
    tree r = right ();
    tree l = left ();
    int d = l.height () - r.height ();
    tree t = *this;

    if ((d == 0) || (d == 1) || (d == -1))
        return t;
```


balance

■ <examples/c++/trees/avl/int/tree.cc>

```
/*  
 * now rotate  
 */  
  
if (d < 0)  
    return t.rotate_left ();  
else if (d > 0)  
    return t.rotate_right ();  
  
return cons (t.root (),  
            r.balance (),  
            l.balance ());  
}
```

Conclusion

- a functional approach can be useful in describing rotate right and left
- a functional approach allows a balance function to be implemented reasonably simply
- at the expense of lost memory, hence the requirement for a garbage collector