



Purely Functional Data structures

Functional Programming

Goals

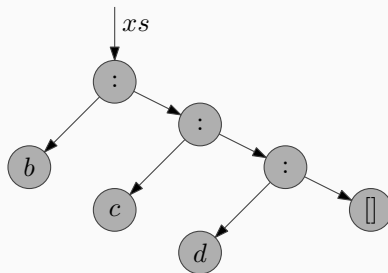
- Know the difference between persistent (purely functional) and ephemeral data structures,
- Be able to use persistent data structures,
- Define and work with custom data types

- What does `x:xs` look like in memory?

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- Suppose that $xs = b:c:d:[]$ for some b,c and d

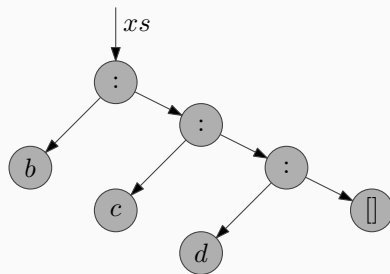
Data Structures in Memory

- What does `xs = b:c:d:[]` look like in memory?



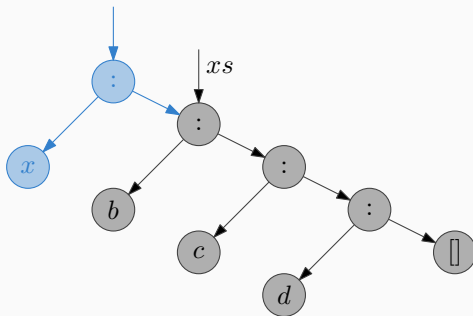
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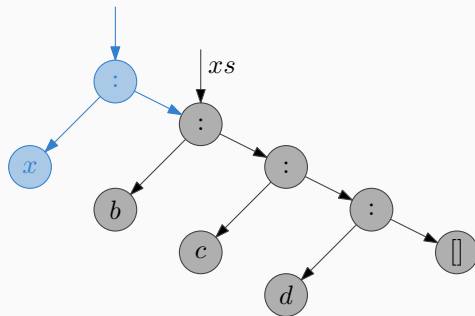
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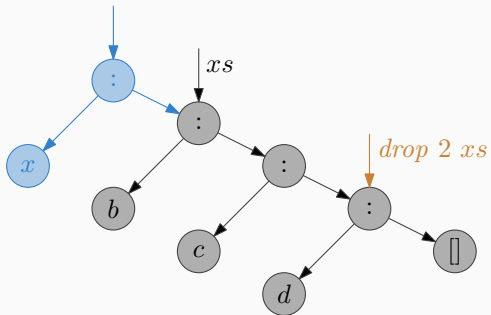
Data Structures in Memory

- What does `drop 2 xs` look like in memory?



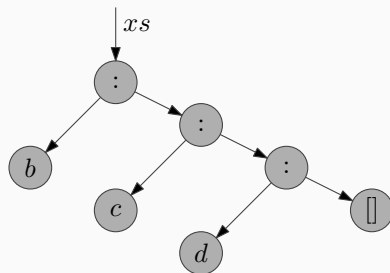
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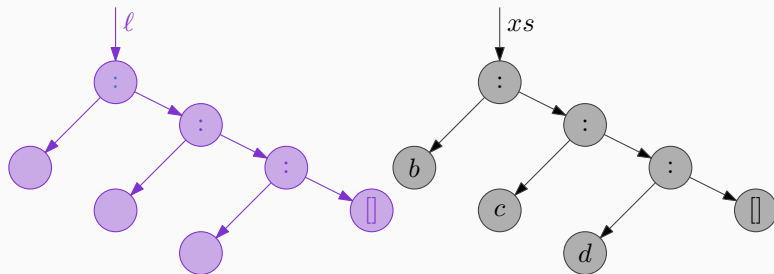
Data Structures in Memory

- What does `1 ++ xs` look like in memory?



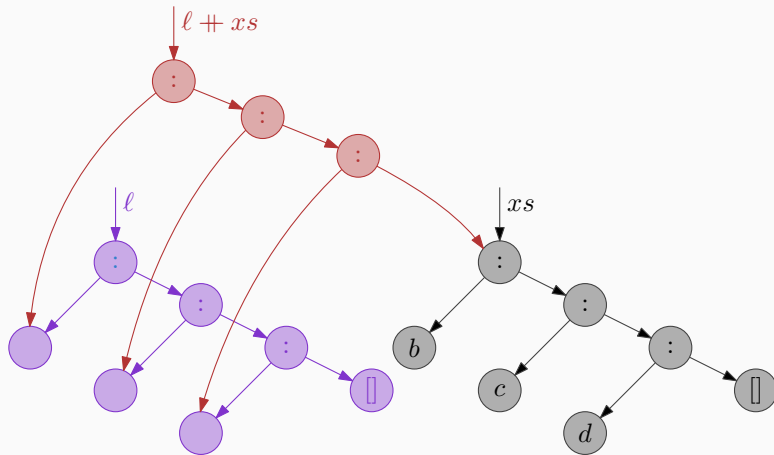
Data Structures in Memory

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Data Structures in Memory

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Persistent vs Ephemeral

- Data structures in which old versions are available are *persistent* data structures.
- Traditional data structures are *ephemeral*.

- Advantages of persistent data structures:
 - Convenient to have both old and new:
 - Separation of concerns;
 - Compute subexpressions independently
 - Output may contain old versions (i.e. tails)

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Yes*!

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[*] for a lot of them

- Store an set S of ordered elements s.t. we can efficiently find successor of a query q .
- The successor of q is the smallest element in S larger or equal to q .

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- Example: $S = \{1, 4, 5, 8, 9, 20\}$, successor of $q = 7$ is 8.

Implementing a Successor DS SuccDS a

- Store the elements of type a in a data structure of type SuccDS a
- What should the type of our succOf function be?

Implementing a Successor DS SuccDS a

- Store the elements of type `a` in a data structure of type `SuccDS a`
- What should the type of our `succOf` function be?

```
succOf :: Ord a => a -> SuccDS a -> Maybe a
```

Implementing a Successor DS: Try 1, Lists

- Idea: Use an (unordered) list

```
type SuccDS a = [a]
```

Implementing a Successor DS: Try 1, Lists

```
succOf      :: Ord a => a -> SuccDS a -> Maybe a
succOf q s  = minimum' [ x | x <- s, x >= q]
  where
    minimum' [] = Nothing
    minimum' xs = Just (minimum xs)
```

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- Running time: $O(n)$

Implementing a Successor DS: Try 2, Ordered Lists

- Idea: Use an *ordered* list.

```
succOf q [] = Nothing
succOf q (x:s) | x < q = succOf q s
               | otherwise = Just x
```


Implementing a Successor DS: Try 2, Ordered Lists

- Idea: Use an *ordered* list.

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succOf q [] = Nothing
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- Does not really help: running time is still $O(n)$.
- We need a better data structure.

Implementing a Successor DS: Try 3, BSTs

- Idea: Use a binary search tree (BST).

```
data Tree a = Leaf
            | Node (Tree a) a (Tree a)
  deriving (Show, Eq)
```

```
type SuccDS a = Tree a
```

Implementing a Successor DS: Try 3, BSTs

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```
data Tree a = Leaf
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```
type SuccDS a = Tree a
```

- Can we list all elements in a `Tree a`?
- Can we test if a `t :: Tree a` is a BST?

Warmup: Listing The elements of a Tree

```
elems          :: Tree a -> [a]
elems Leaf     = []
elems (Node l x r) = elems l ++ [x] ++ elems r
```

Warmup: Testing if a Tree is a BST?

```
isBST :: Ord a => Tree a -> Bool
isBST Leaf = True
isBST (Node l x r) = all (<= x) (elems l)
                    && all (>= x) (elems r)
                    && isBST l && isBST r
```

- This implementation uses $O(n^2)$ time.
- Exercise: write an implementation that runs in $O(n)$ time.

Implementing a Successor DS: Queries

```
succOf q Leaf = Nothing
succOf q (Node l x r) | x < q = succOf q r
                      | otherwise =
    case succOf q l of
      Nothing -> Just x
      Just sq  -> Just sq
```

Implementing a Successor DS: Queries

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Nice if the input tree happens to be balanced, i.e. of height $O(\log n)$

Making Balanced Trees

- Suppose that the input is a sorted list, how to build a balanced tree?

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```
buildBalanced :: [a] -> Tree a
```

```
buildBalanced [] = Leaf
```

```
buildBalanced xs = Node l x r
```

where

```
  m = length xs `div` 2
```

```
  (ls,x:rs) = splitAt m xs
```

```
  l = buildBalanced ls
```

```
  r = buildBalanced rs
```

- Running time: $O(n \log n)$.

Dynamic Successor: Insert

- Can we add new elements to the set S ?

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```
insert      :: Ord a => a -> Tree a -> Tree a
insert x Leaf = Node Leaf x Leaf
insert x t@(Node l y r)
  | x < y    = Node (insert x l) y r
  | x == y   = t
  | otherwise = Node l y (insert x r)
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Dynamic Successor: Insert

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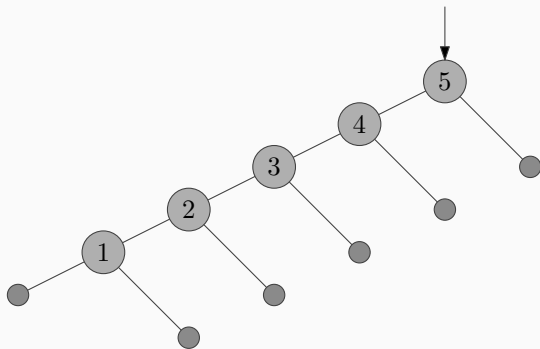
- Not just insert x l!
- Note that we are building new trees!

May unbalance the tree

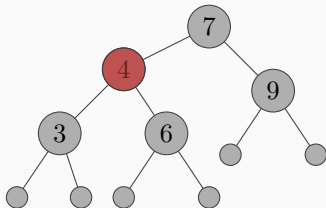
- Repeatedly inserting elements unbalances the tree

```
> foldr insert Leaf [1..5]
```

```
Node (Node (Node (Node (Node Leaf 1 Leaf) 2 Leaf) 3 Leaf) 4 Leaf) 5 Leaf
```

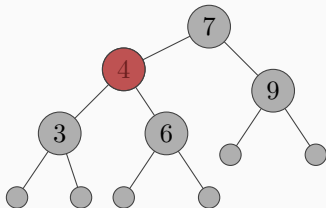


Self balancing trees: Red Black Trees



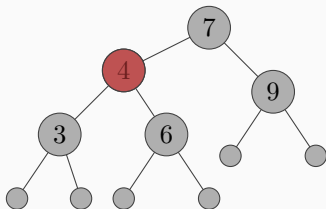
- Properties:
 - 1) leaves are black
 - 2) root is black
 - 3) red nodes have black children
 - 4) for any node, all paths to leaves have the same number of black children.

Self balancing trees: Red Black Trees



- Properties:
 - 1) leaves are black
 - 2) root is black
 - 3) red nodes have black children
 - 4) for any node, both children have the same *blackheight*
- blackHeight of a node = number of black children on any path from that node to its leaves.

Self balancing trees: Red Black Trees



- Properties:
 - 1) leaves are black
 - 2) root is black
 - 3) red nodes have black children
 - 4) for any node, both children have the same *blackheight*
- Support queries and updates in $O(\log n)$ time.

Red Black Trees in Haskell

```
data Color = Red | Black deriving (Show,Eq)
```

```
data RBTREE a = Leaf  
              | Node Color (RBTREE a) a (RBTREE a)  
              deriving (Show,Eq)
```

- Enforces property 1. Other properties are more difficult to enforce in the type.

- succOf more or less the same as before.
- Insert:
 - Make sure black heights remain ok by replacing a black leaf by a red node.
 - The only issue is red,red violations.
 - Allow red,red violations with the root, but not below that.
 - Recolor the root black at the end.

Implementing Insert

```
insert  :: Ord a => a -> RBTREE a -> RBTREE a
```

```
insert x = blackenRoot . insert' x
```

```
insert' :: Ord a => a -> RBTREE a -> RBTREE a
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```
blackenRoot :: RBTREE a -> RBTREE a
```

```
blackenRoot Leaf = Leaf
```

```
blackenRoot (Node _ l y r) = Node Black l y r
```

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insert'      :: Ord a => a -> RBTREE a -> RBTREE a  
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insert' x t@(Node c l y r)
  | x < y      = Node c (insert' x l) y r
  | x == y     = t
  | otherwise  = Node c l y (insert' x r)
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```

As before, this creates an unbalanced tree. So, what's left is to rebalance the newly created trees.

Implementing Insert'

```
insert'      :: Ord a => a -> RBTREE a -> RBTREE a
insert' x Leaf = Node Red Leaf x Leaf

insert' x t@(Node c l y r)
  | x < y      = balance c (insert' x l) y r
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Implementing Insert'

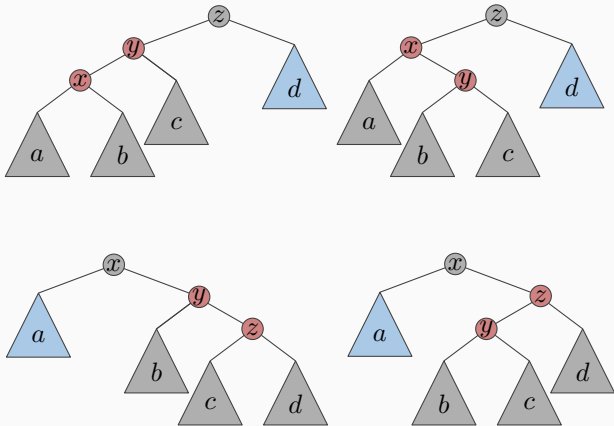
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balance :: Color -> RBTREE a -> a -> RBTREE a
         -> RBTREE a
```

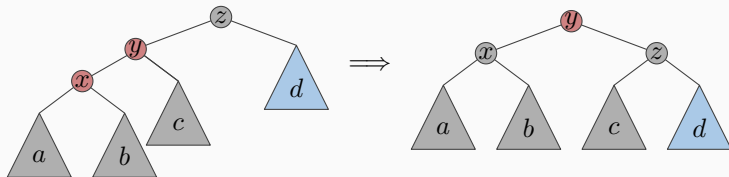
Rebalancing

- The only potential issue is two red nodes near the root.
- There are only four configurations:



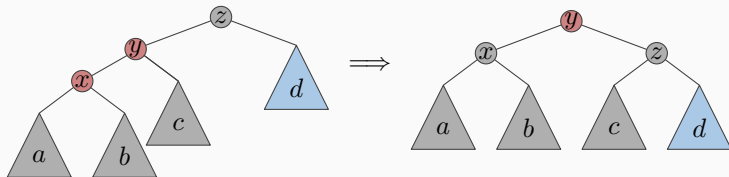
Rebalancing

- Make the root red, and its children black:



Rebalancing

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balance Black (Node Red (Node Red a x b) y c) z d =
Node Red (Node Black a x b) y (Node Black c z d)

Rebalancing code

- Other cases are symmetric:

```
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```

```
    Node Red (Node Black a x b) y (Node Black c z d)
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```

```
balance c l x r =
```

```
    Node c l x r
```

- What if we also want to remove elements from S ?

- What if we also want to remove elements from S ?
- Possible in $O(\log n)$ time with Red-Black trees, but a bit more messy.

- Self balancing BST Implementation available in `Data.Set`
- Often useful to store additional information: `Data.Map`.

```
lookup :: Ord k => k -> Map k v -> Maybe v
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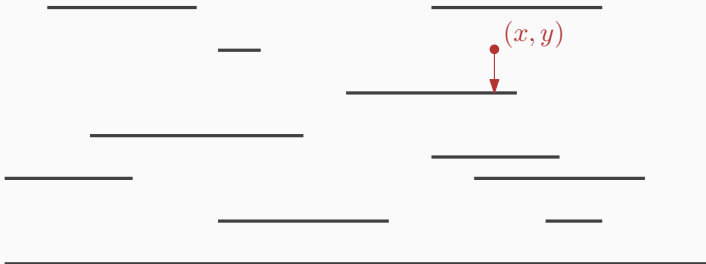
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- Finite Sequences: `Data.Sequence`, allow fast access to front and back.
- All these data structures are persistent.

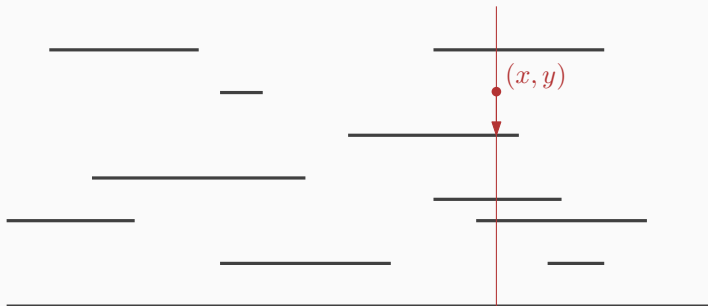
Example Application: Point Location

- Can we quickly find the platform directly below Mario at (x, y) ?



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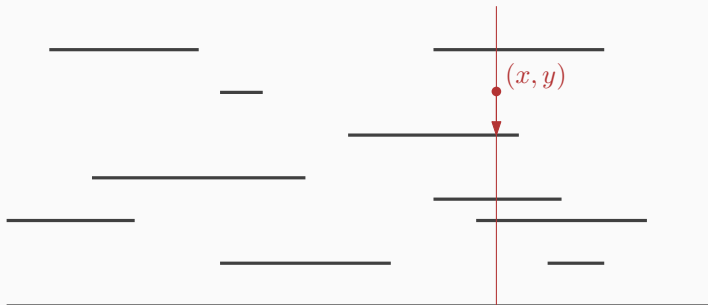
- Can we quickly find the platform directly below Mario at (x, y) ?



- Easy if we had the platforms intersecting the vertical line at x in top-to-bottom order in a Set or Map: find successor of y .

Example Application: Point Location

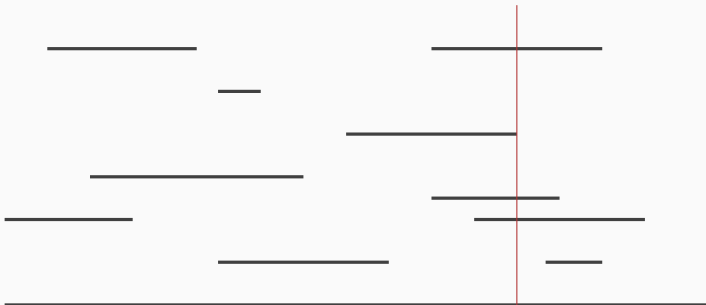
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- What happens when vertical line starts/stops to intersect a platform?

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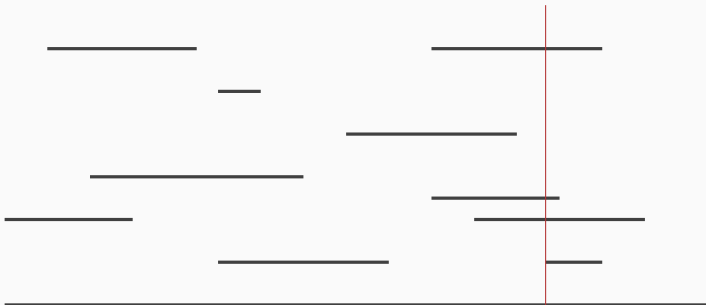
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- Since Set is persistent, old versions remain in tact. Store them in a Map.

Example Application: Point Location

- Can we quickly find the platform directly below Mario at (x, y) ?
- What happens when vertical line starts/stops to intersect a platform?
- Add or remove a platform from the Set
- Since Set is persistent, old versions remain in tact. Store them in a Map.
- To answer a query: go to the version at time x using a successor query, and find successor of y .

Homework: Verifying Red-Black Tree Properties

- Write a function `validRBTREE :: RBTREE a -> Bool` that checks if a given `RBTREE a` satisfies all red-black tree properties.