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3.3 BALANCED SEARCH TREES

- ▶ *2-3 search trees*
- ▶ *red-black BSTs*
- ▶ *B-trees*

Symbol table review

implementation	worst-case cost (after N inserts)			average case (after N random inserts)			ordered iteration?	key interface
	search	insert	delete	search hit	insert	delete		
sequential search (unordered 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	1.39 lg N	1.39 lg N	?	yes	compareTo()
goal	log N	log N	log N	log N	log N	log N	yes	compareTo()

Challenge. Guarantee performance.

This lecture. 2-3 trees, left-leaning red-black BSTs, B-trees.



3.3 BALANCED SEARCH TREES

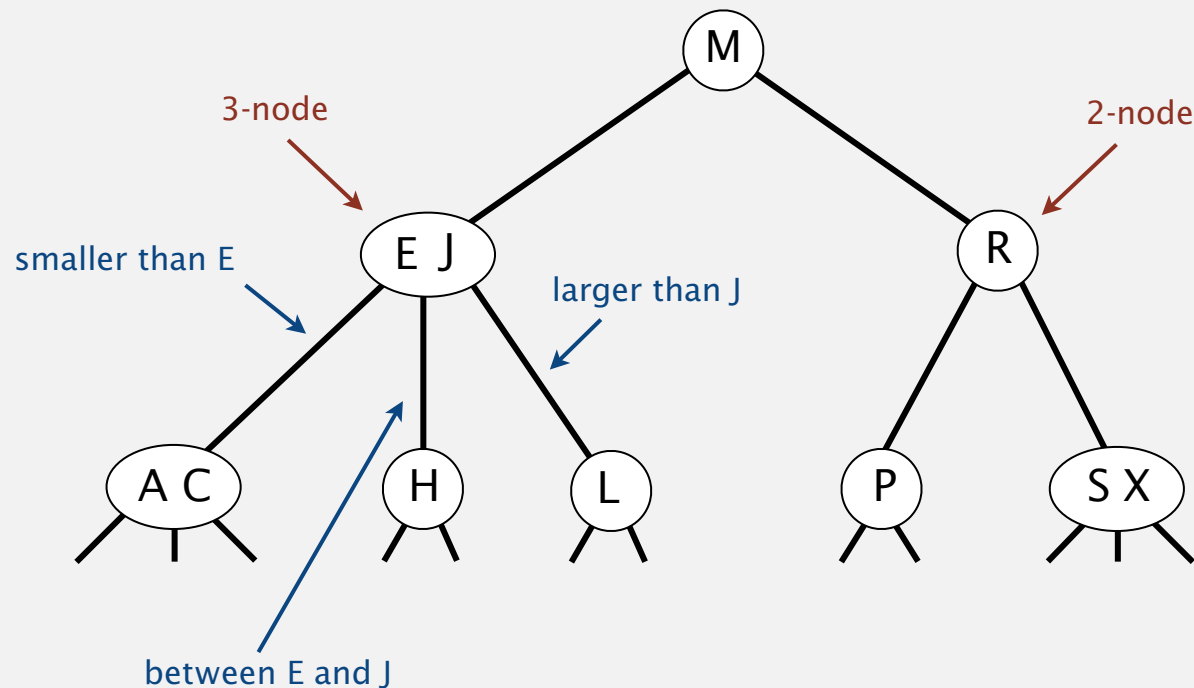
- ▶ 2-3 *search trees*
- ▶ *red-black BSTs*
- ▶ *B-trees*

2-3 tree

Allow 1 or 2 keys per node.

- 2-node: one key, two children.
- 3-node: two keys, three children.

Symmetric order. Inorder traversal yields keys in ascending order.



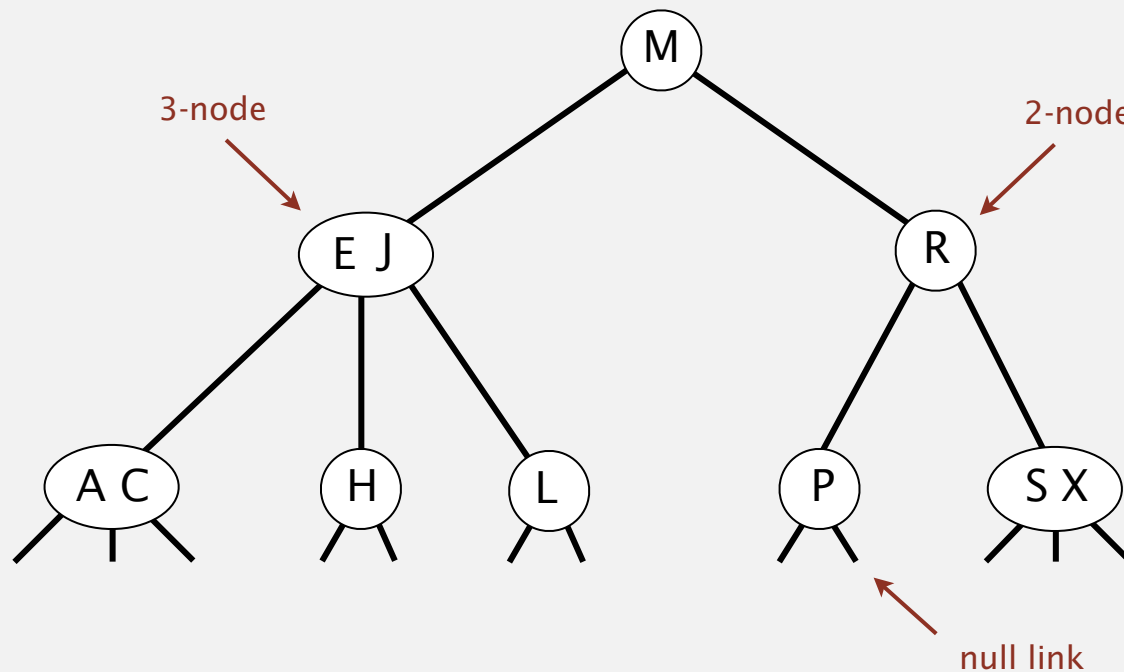
2-3 tree

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Perfect balance. Every path from root to null link has same length.



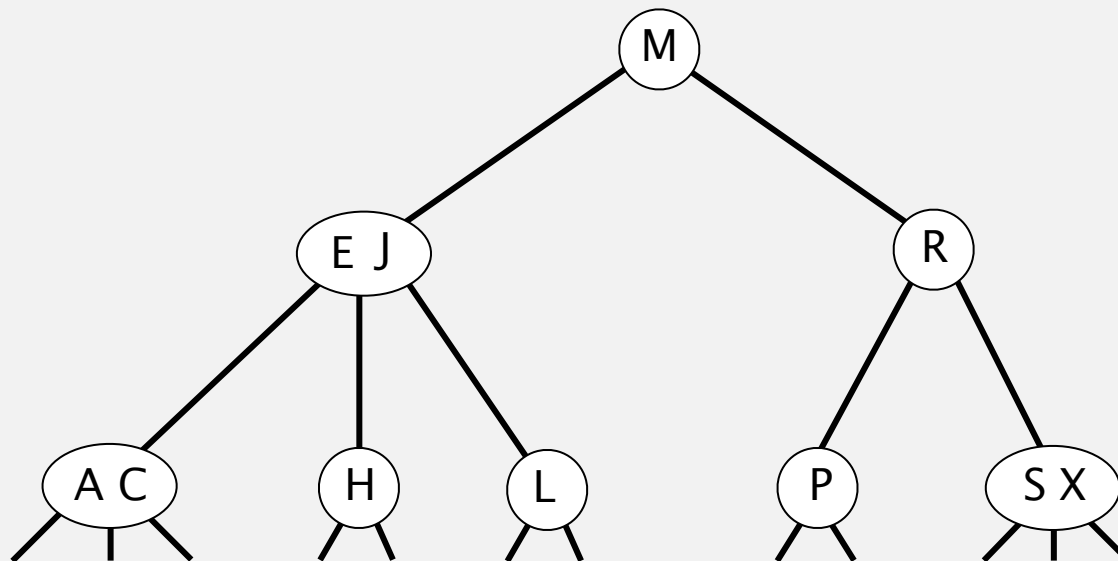
2-3 tree demo

Search.

- Compare search key against keys in node.
- Find interval containing search key.
- Follow associated link (recursively).



search for H

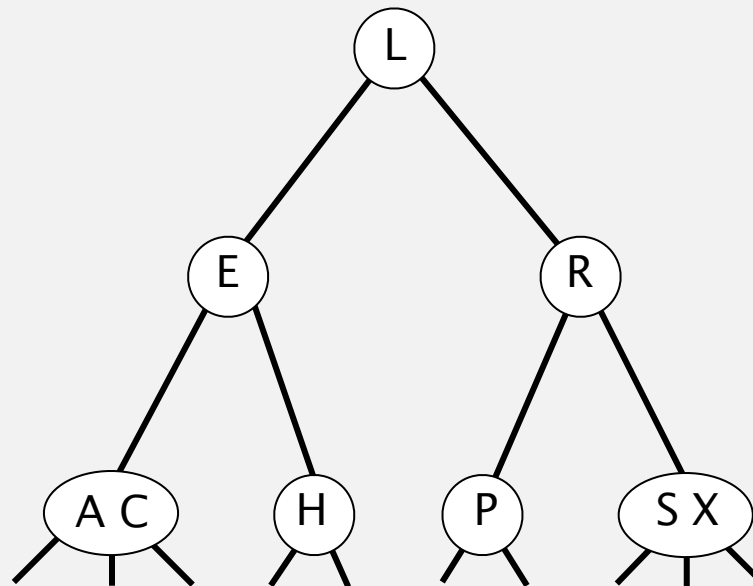


2-3 tree demo

Insertion into a 3-node at bottom.

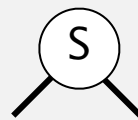
- Add new key to 3-node to create temporary 4-node.
- Move middle key in 4-node into parent.
- Repeat up the tree, as necessary.
- If you reach the root and it's a 4-node, split it into three 2-nodes.

insert L



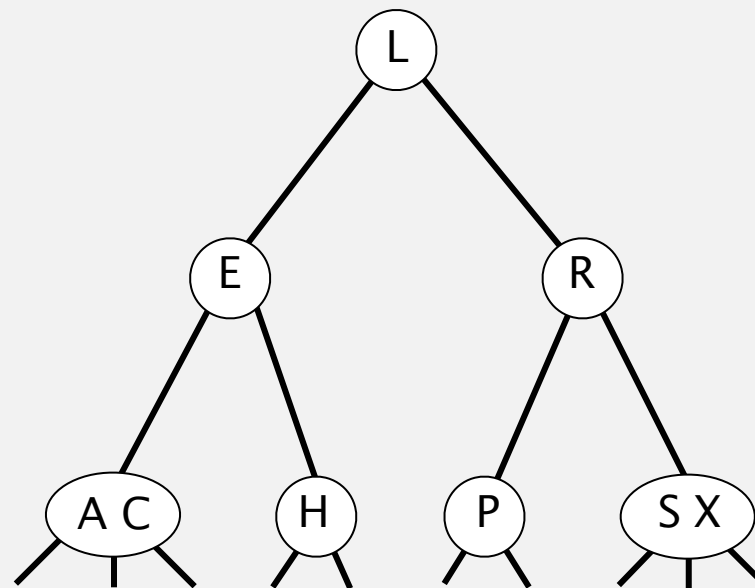
2-3 tree construction demo

insert S



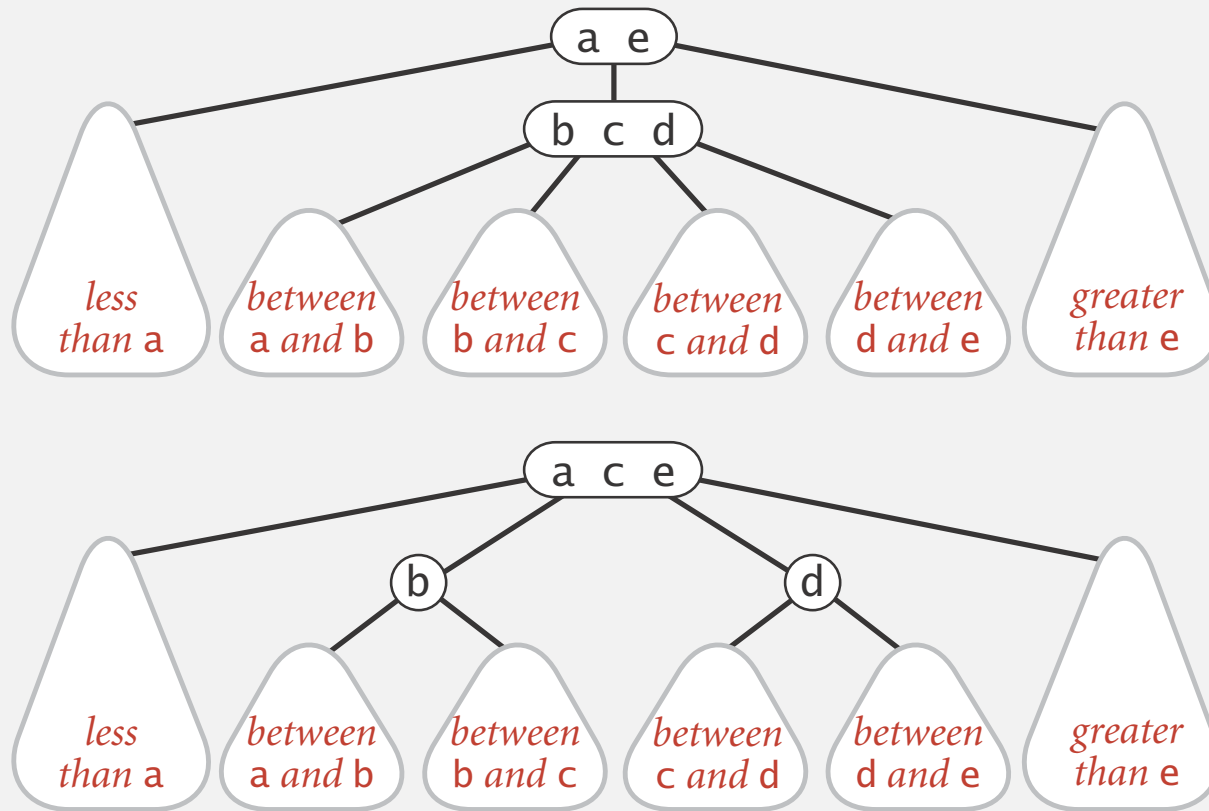
2-3 tree construction demo

2-3 tree



Local transformations in a 2-3 tree

Splitting a 4-node is a **local** transformation: constant number of operations.



Global properties in a 2-3 tree

Invariants. Maintains symmetric order and perfect balance.

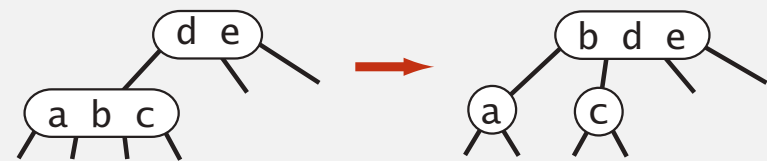
Pf. Each transformation maintains symmetric order and perfect balance.

root



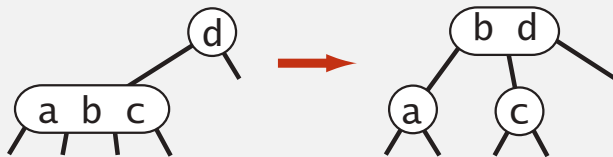
parent is a 3-node

left

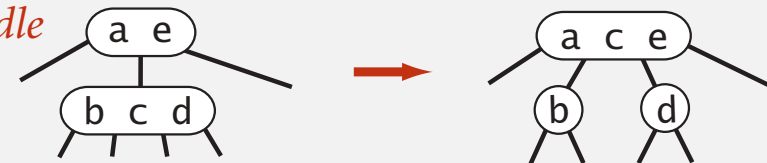


parent is a 2-node

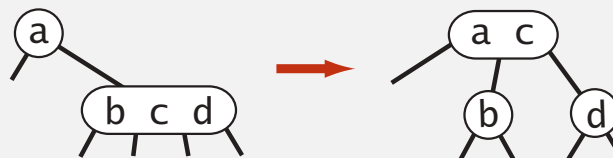
left



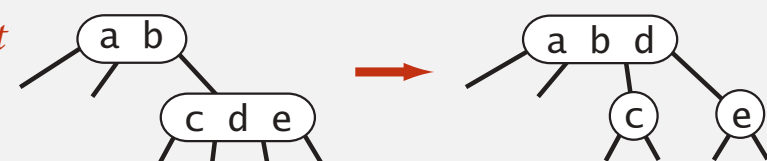
middle



right

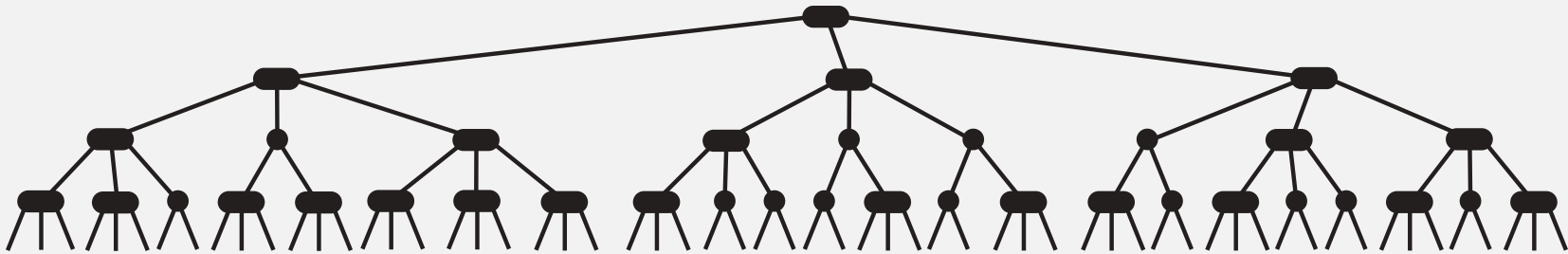


right



2-3 tree: performance

Perfect balance. Every path from root to null link has same length.

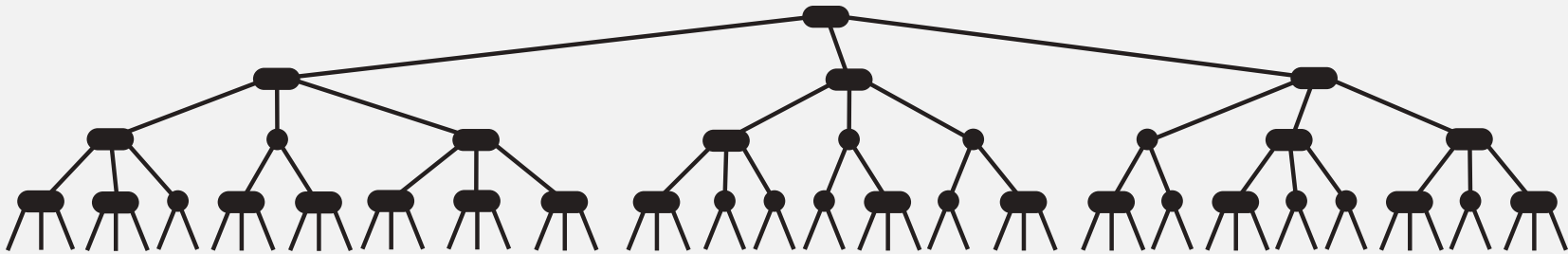


Tree height.

- Worst case:
- Best case:

2-3 tree: performance

Perfect balance. Every path from root to null link has same length.



Tree height.

- Worst case: $\lg N$. [all 2-nodes]
- Best case: $\log_3 N \approx .631 \lg N$. [all 3-nodes]
- Between 12 and 20 for a million nodes.
- Between 18 and 30 for a billion nodes.

Guaranteed **logarithmic** performance for search and insert.

ST implementations: summary

implementation	worst-case cost (after N inserts)			average case (after N random inserts)			ordered iteration?	key interface
	search	insert	delete	search hit	insert	delete		
sequential search (unordered list)	N	N	N	N/2	N	N/2	no	equals()
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BST	N	N	N	1.39 lg N	1.39 lg N	?	yes	compareTo()
2-3 tree	$c \lg N$	$c \lg N$	$c \lg N$	$c \lg N$	$c \lg N$	$c \lg N$	yes	compareTo()



constants depend upon implementation

2-3 tree: implementation?

Direct implementation is complicated, because:

- Maintaining multiple node types is cumbersome.
- Need multiple compares to move down tree.
- Need to move back up the tree to split 4-nodes.
- Large number of cases for splitting.

Bottom line. Could do it, but there's a better way.



3.3 BALANCED SEARCH TREES

- ▶ 2-3 *search trees*
- ▶ *red-black BSTs*
- ▶ *B-trees*

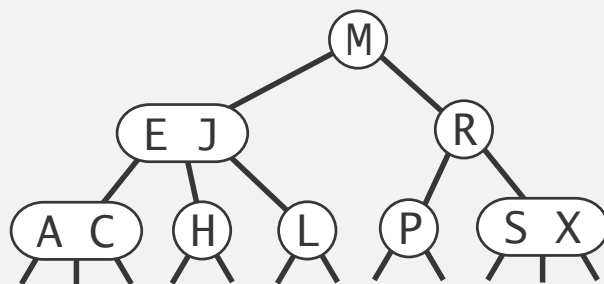
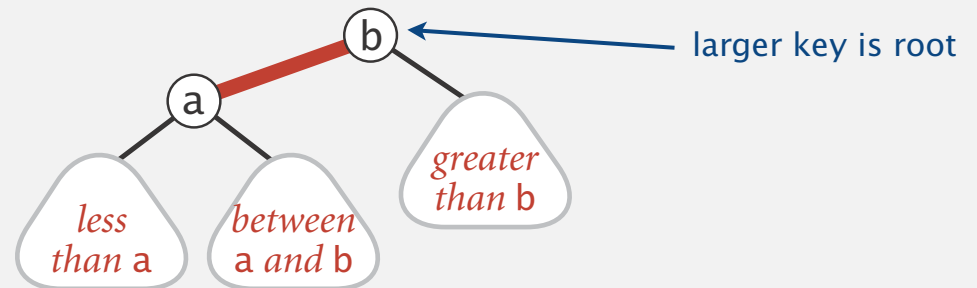
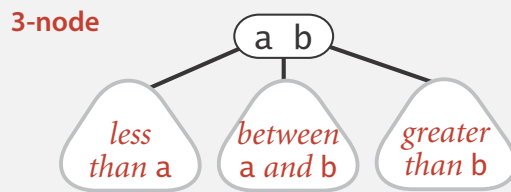


3.3 BALANCED SEARCH TREES

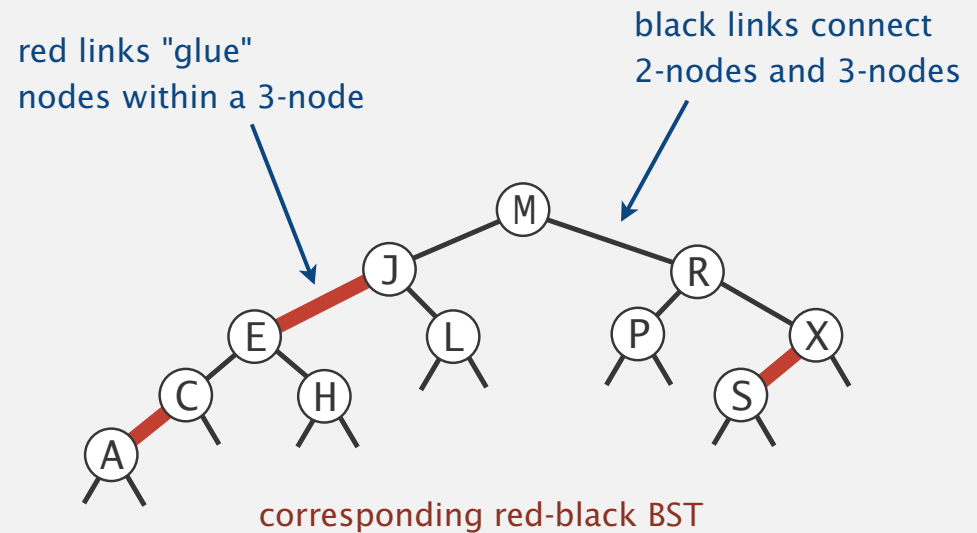
- ▶ *2-3 search trees*
- ▶ *red-black BSTs*
- ▶ *B-trees*

Left-leaning red-black BSTs (Guibas-Sedgwick 1979 and Sedgwick 2007)

1. Represent 2–3 tree as a BST.
2. Use "internal" left-leaning links as "glue" for 3–nodes.



2-3 tree

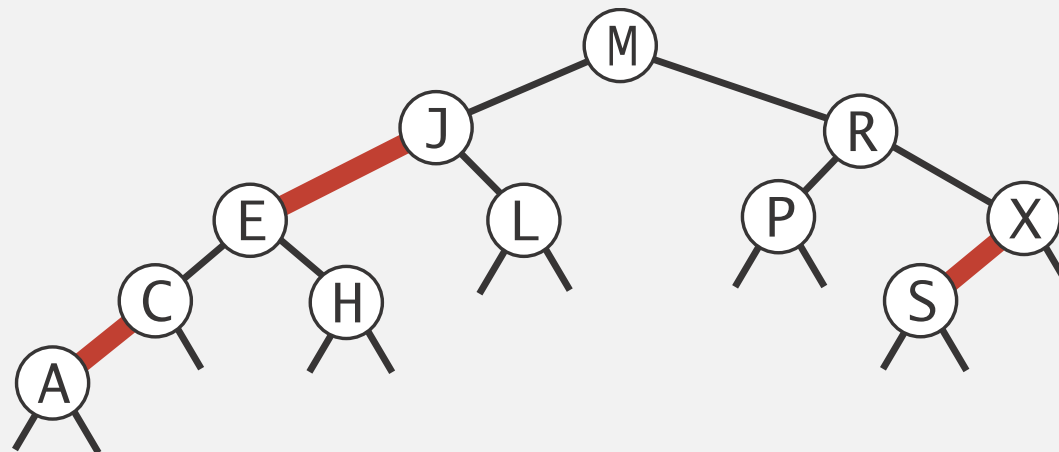


An equivalent definition

A BST such that:

- No node has two red links connected to it.
- Every path from root to null link has the same number of black links.
- Red links lean left.

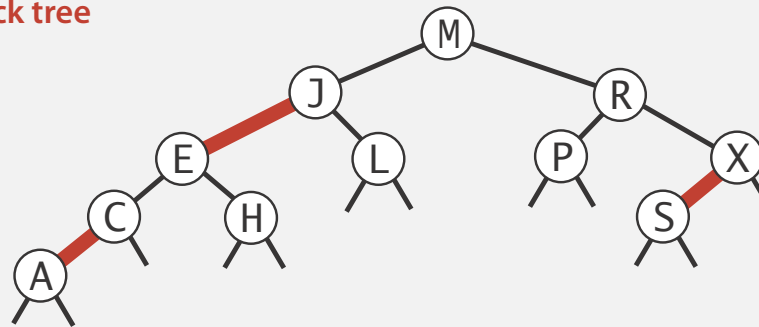
↖
"perfect black balance"



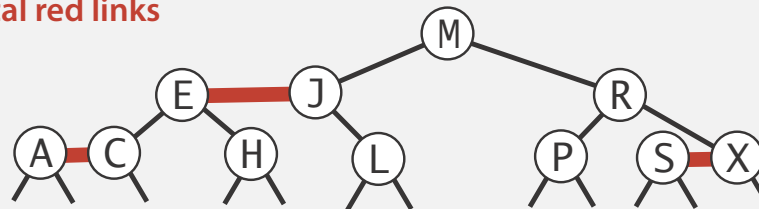
Left-leaning red-black BSTs: 1-1 correspondence with 2-3 trees

Key property. 1–1 correspondence between 2–3 and LLRB.

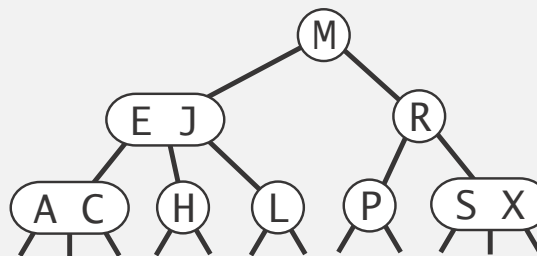
red-black tree



horizontal red links



2-3 tree

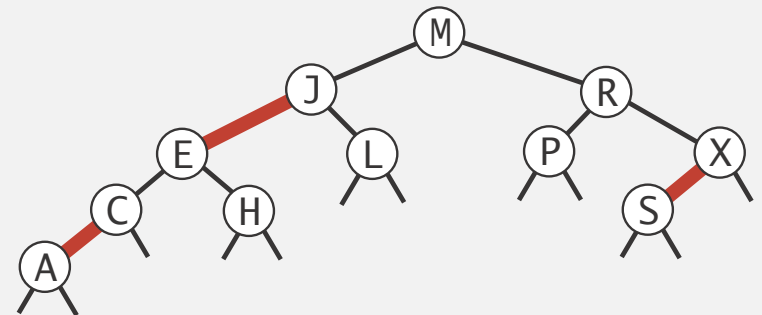


Search implementation for red-black BSTs

Observation. Search is the same as for elementary BST (ignore color).

but runs faster
because of better balance

```
public Val 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;
}
```



Remark. Most other ops (e.g., floor, iteration, selection) are also identical.

Red-black BST representation

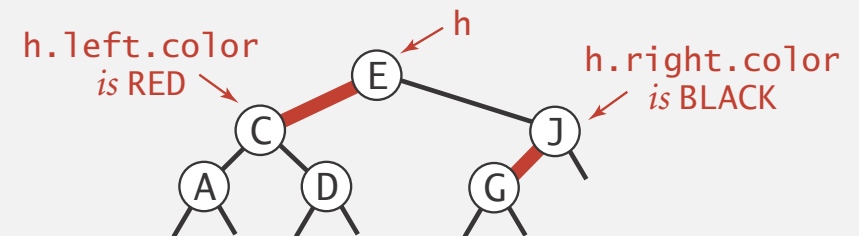
Each node is pointed to by precisely one link (from its parent) \Rightarrow
can encode color of links in nodes.

```
private static final boolean RED    = true;  
private static final boolean BLACK = false;
```

```
private class Node  
{  
    Key key;  
    Value val;  
    Node left, right;  
    boolean color; // color of parent link  
}
```

```
private boolean isRed(Node x)  
{  
    if (x == null) return false;  
    return x.color == RED;  
}
```

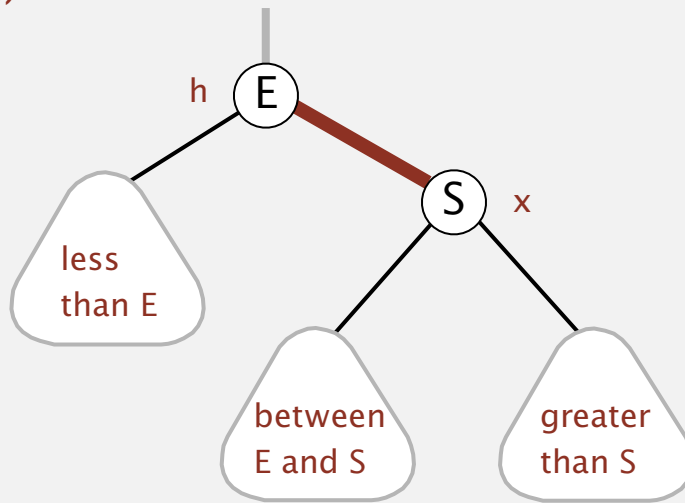
← null links are black



Elementary red-black BST operations

Left rotation. Orient a (temporarily) right-leaning red link to lean left.

rotate E left
(before)

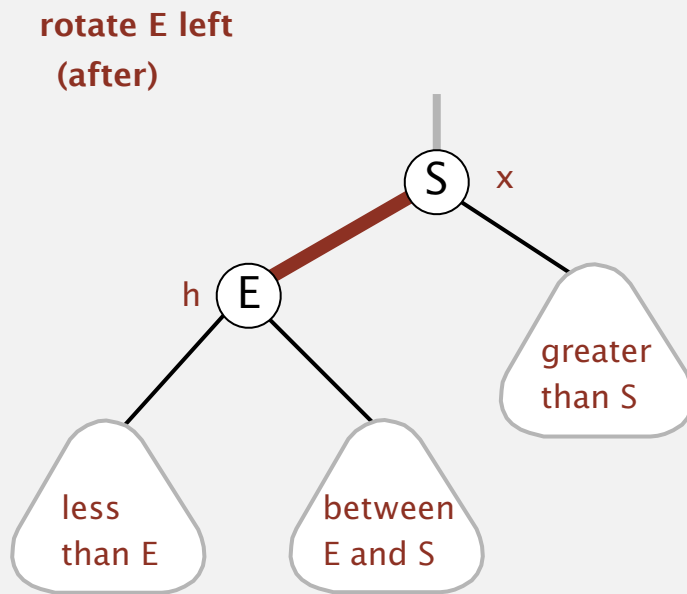


```
private Node rotateLeft(Node h)
{
    assert isRed(h.right);
    Node x = h.right;
    h.right = x.left;
    x.left = h;
    x.color = h.color;
    h.color = RED;
    return x;
}
```

Invariants. Maintains symmetric order and perfect black balance.

Elementary red-black BST operations

Left rotation. Orient a (temporarily) right-leaning red link to lean left.

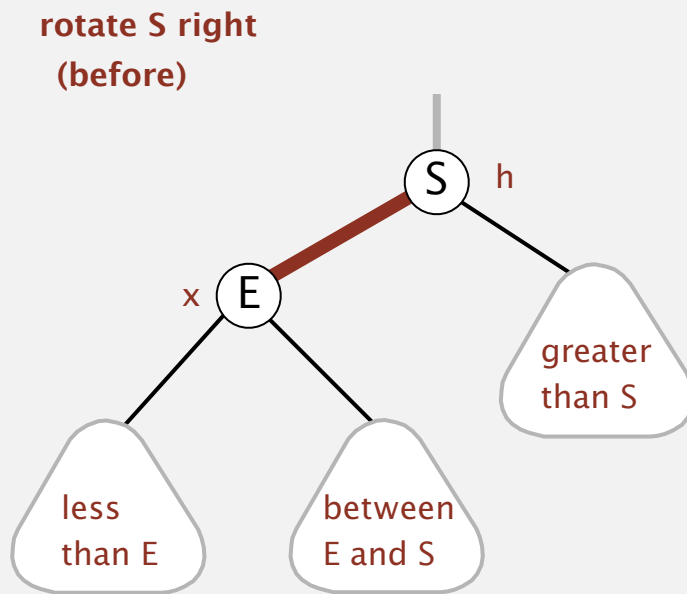


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    h.right = x.left;
    x.left = h;
    x.color = h.color;
    h.color = RED;
    return x;
}
```

Invariants. Maintains symmetric order and perfect black balance.

Elementary red-black BST operations

Right rotation. Orient a left-leaning red link to (temporarily) lean right.



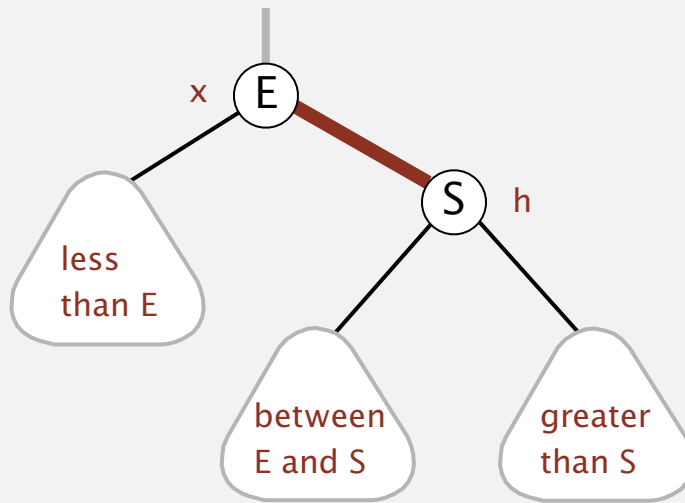
```
private Node rotateRight(Node h)
{
    assert isRed(h.left);
    Node x = h.left;
    h.left = x.right;
    x.right = h;
    x.color = h.color;
    h.color = RED;
    return x;
}
```

Invariants. Maintains symmetric order and perfect black balance.

Elementary red-black BST operations

Right rotation. Orient a left-leaning red link to (temporarily) lean right.

rotate S right
(after)

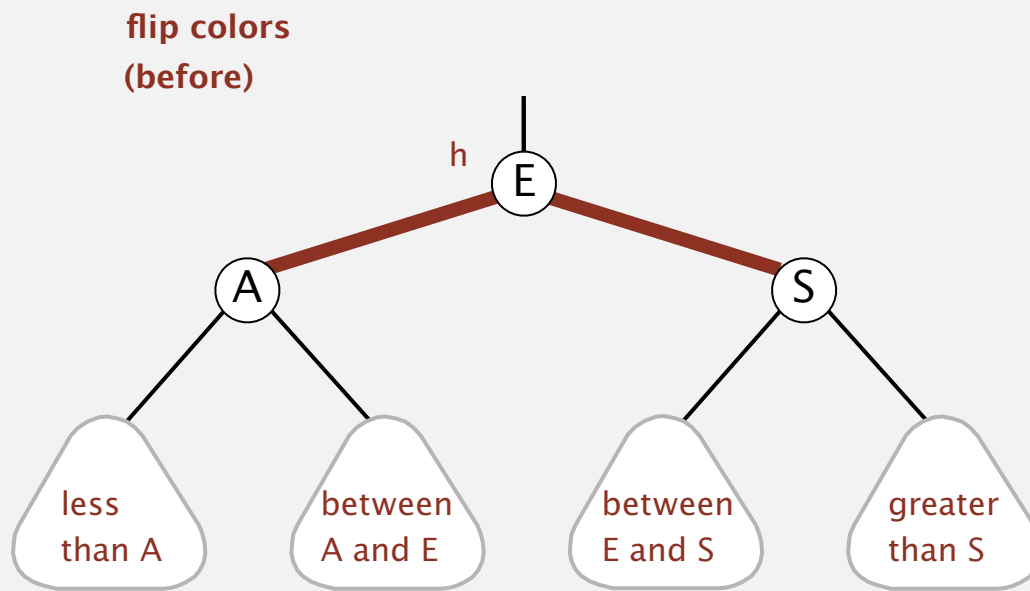


```
private Node rotateRight(Node h)
{
    assert isRed(h.left);
    Node x = h.left;
    h.left = x.right;
    x.right = h;
    x.color = h.color;
    h.color = RED;
    return x;
}
```

Invariants. Maintains symmetric order and perfect black balance.

Elementary red-black BST operations

Color flip. Recolor to split a (temporary) 4-node.

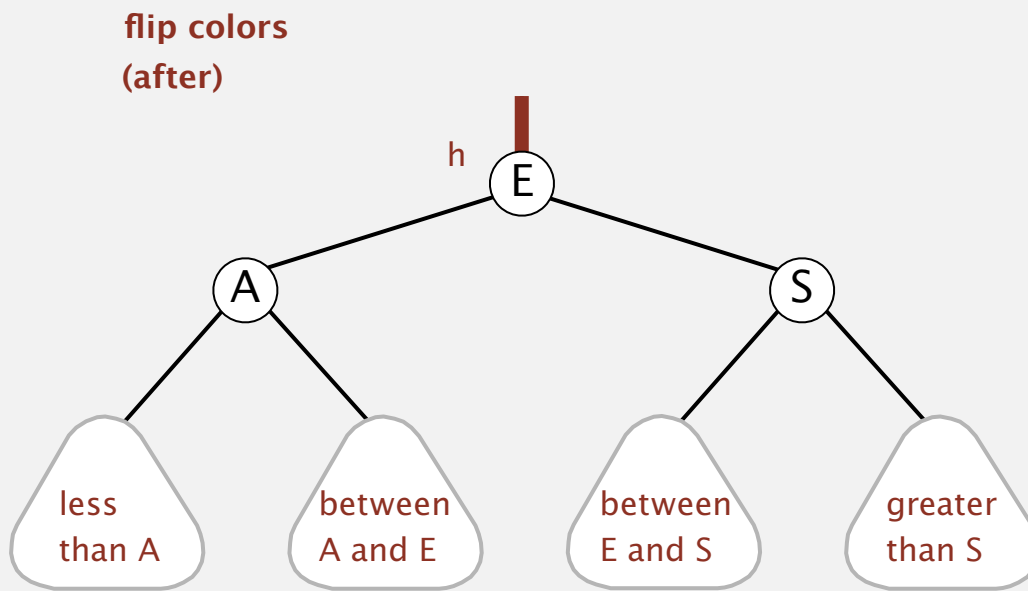


```
private void flipColors(Node h)
{
    assert !isRed(h);
    assert isRed(h.left);
    assert isRed(h.right);
    h.color = RED;
    h.left.color = BLACK;
    h.right.color = BLACK;
}
```

Invariants. Maintains symmetric order and perfect black balance.

Elementary red-black BST operations

Color flip. Recolor to split a (temporary) 4-node.



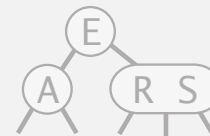
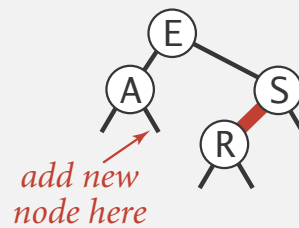
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}
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Invariants. Maintains symmetric order and perfect black balance.

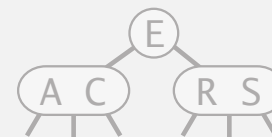
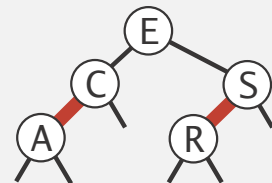
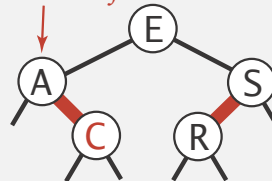
Insertion in a LLRB tree: overview

Basic strategy. Maintain 1-1 correspondence with 2-3 trees by applying elementary red-black BST operations.

insert C



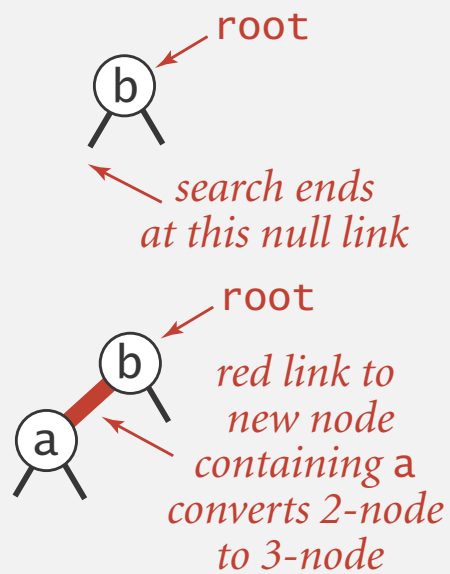
right link red
so rotate left



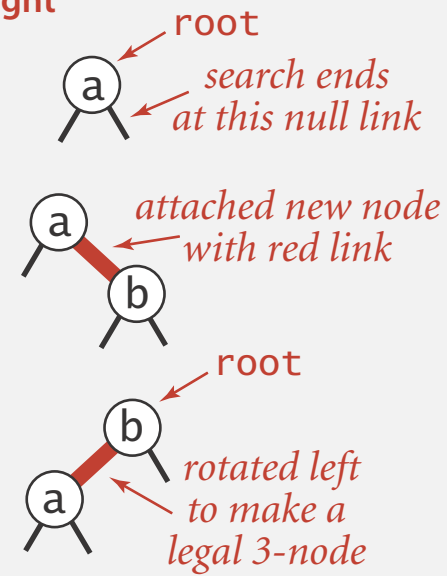
Insertion in a LLRB tree

Warmup 1. Insert into a tree with exactly 1 node.

left



right

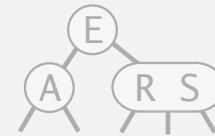
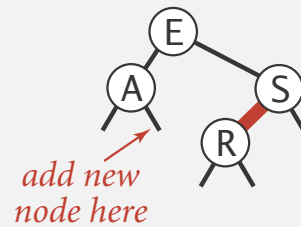


Insertion in a LLRB tree

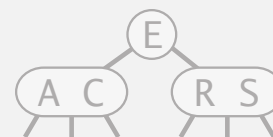
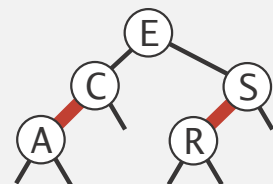
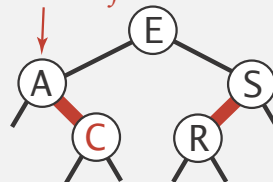
Case 1. Insert into a 2-node at the bottom.

- Do standard BST insert; color new link red.
- If new red link is a right link, rotate left.

insert C



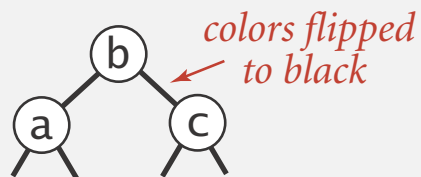
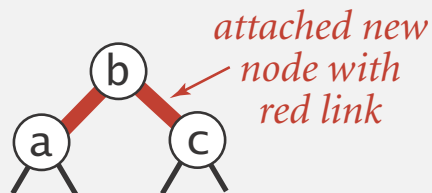
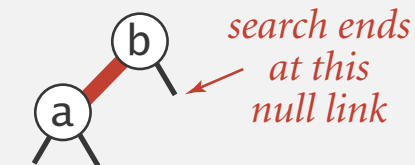
right link red
so rotate left



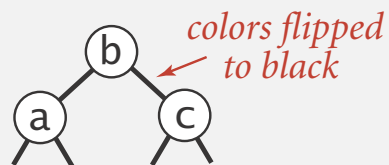
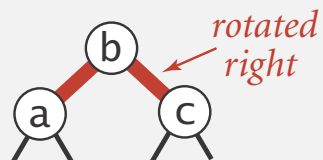
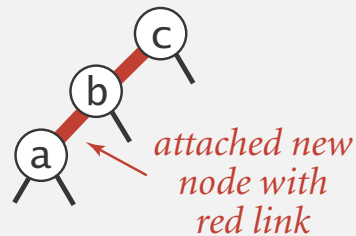
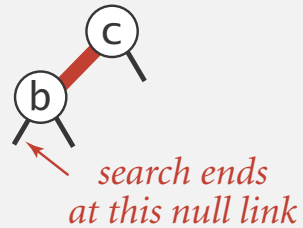
Insertion in a LLRB tree

Warmup 2. Insert into a tree with exactly 2 nodes.

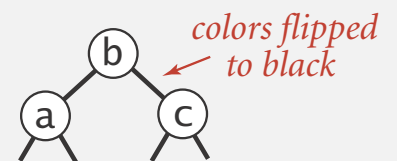
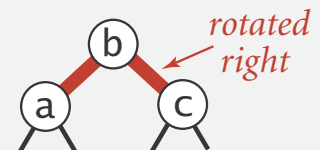
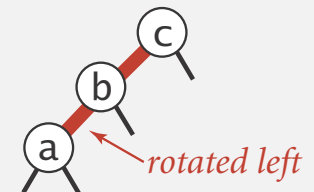
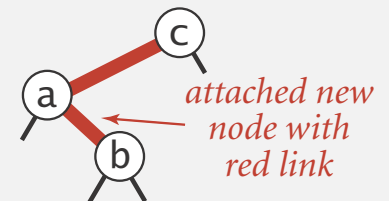
larger



smaller



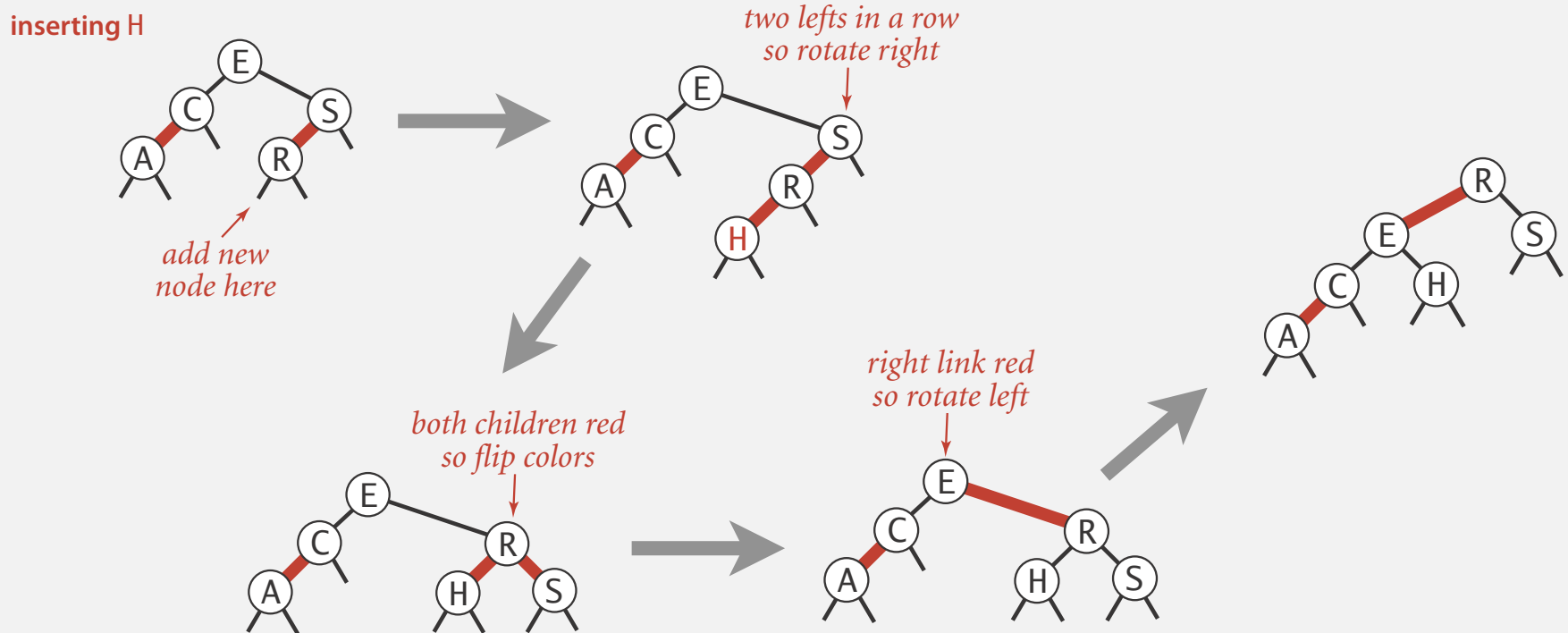
between



Insertion in a LLRB tree

Case 2. Insert into a 3-node at the bottom.

- Do standard BST insert; color new link red.
- Rotate to balance the 4-node (if needed).
- Flip colors to pass red link up one level.
- Rotate to make lean left (if needed).

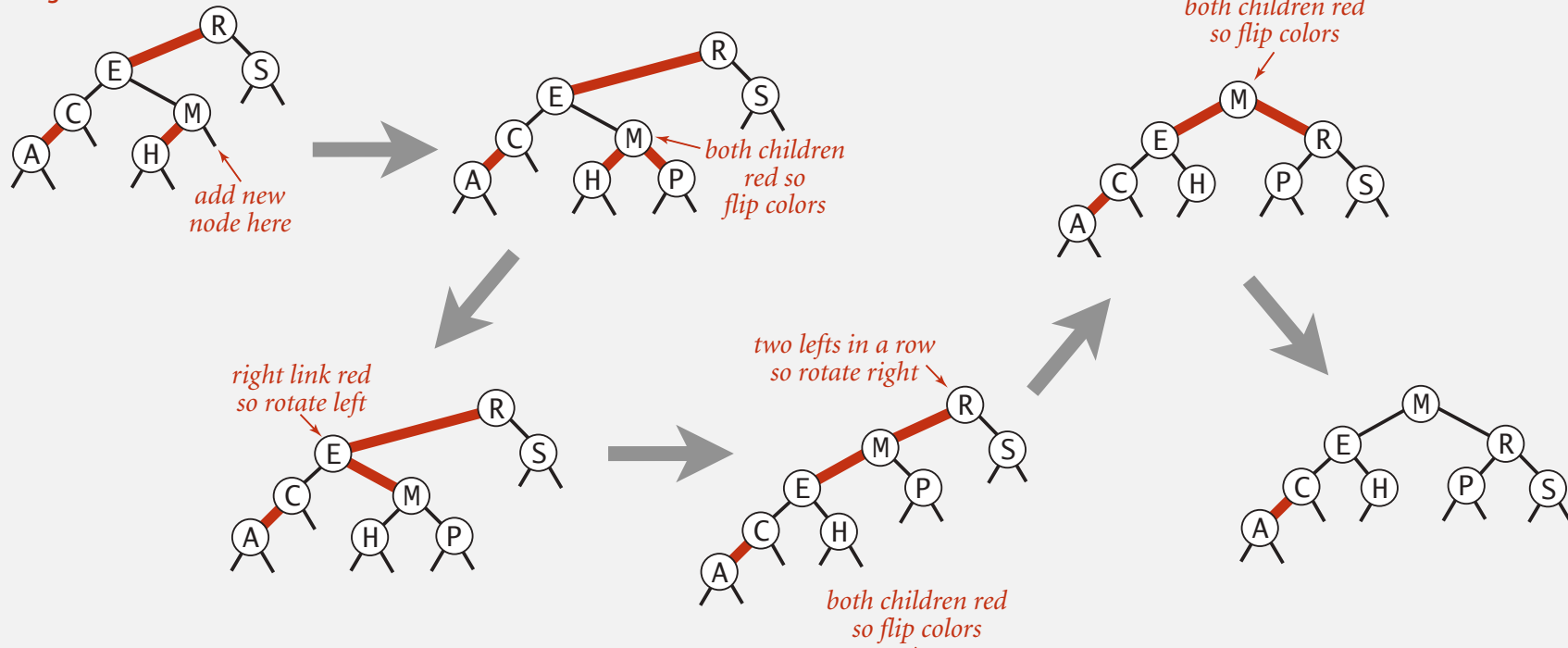


Insertion in a LLRB tree: passing red links up the tree

Case 2. Insert into a 3-node at the bottom.

- Do standard BST insert; color new link red.
- Rotate to balance the 4-node (if needed).
- Flip colors to pass red link up one level.
- Rotate to make lean left (if needed).
- Repeat case 1 or case 2 up the tree (if needed).

inserting P



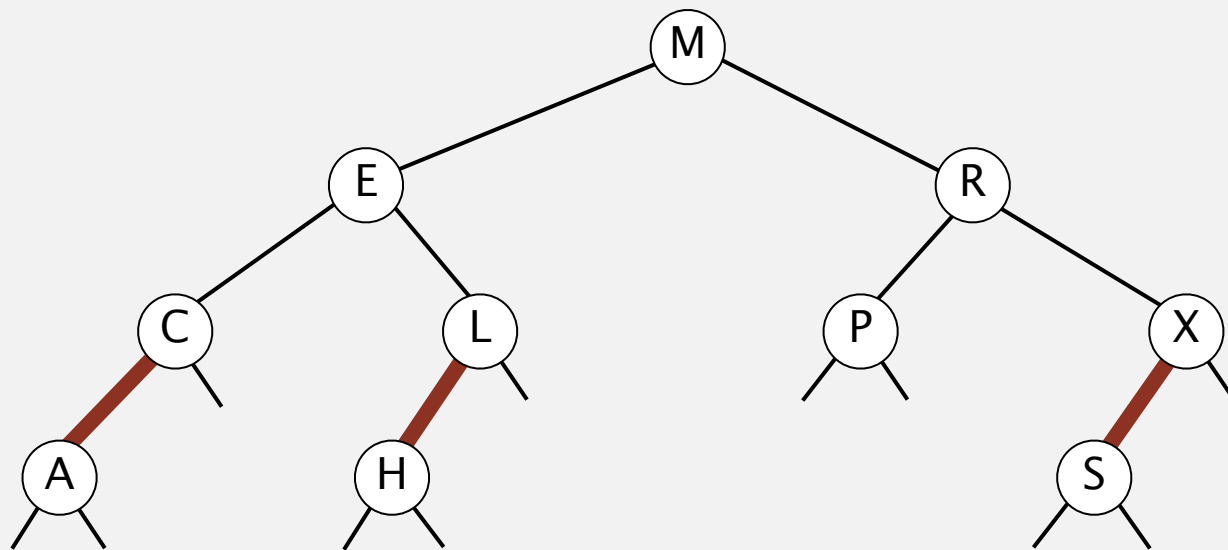
Red-black BST construction demo

insert S



Red-black BST construction demo

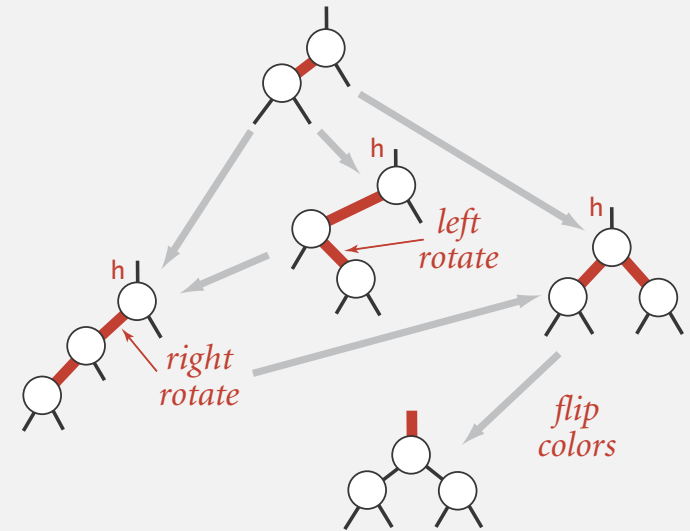
red-black BST



Insertion in a LLRB tree: Java implementation

Same code for all cases.

- Right child red, left child black: **rotate left**.
- Left child, left-left grandchild red: **rotate right**.
- Both children red: **flip colors**.



```
private Node put(Node h, Key key, Value val)
{
```

```
    if (h == null) return new Node(key, val, RED);
```

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

```
    if (cmp < 0) h.left = put(h.left, key, val);
```

```
    else if (cmp > 0) h.right = put(h.right, key, val);
```

```
    else if (cmp == 0) h.val = val;
```

```
    if (isRed(h.right) && !isRed(h.left)) h = rotateLeft(h);
```

```
    if (isRed(h.left) && isRed(h.left.left)) h = rotateRight(h);
```

```
    if (isRed(h.left) && isRed(h.right)) flipColors(h);
```

```
    return h;
```

```
}
```

← insert at bottom
(and color it red)

← lean left

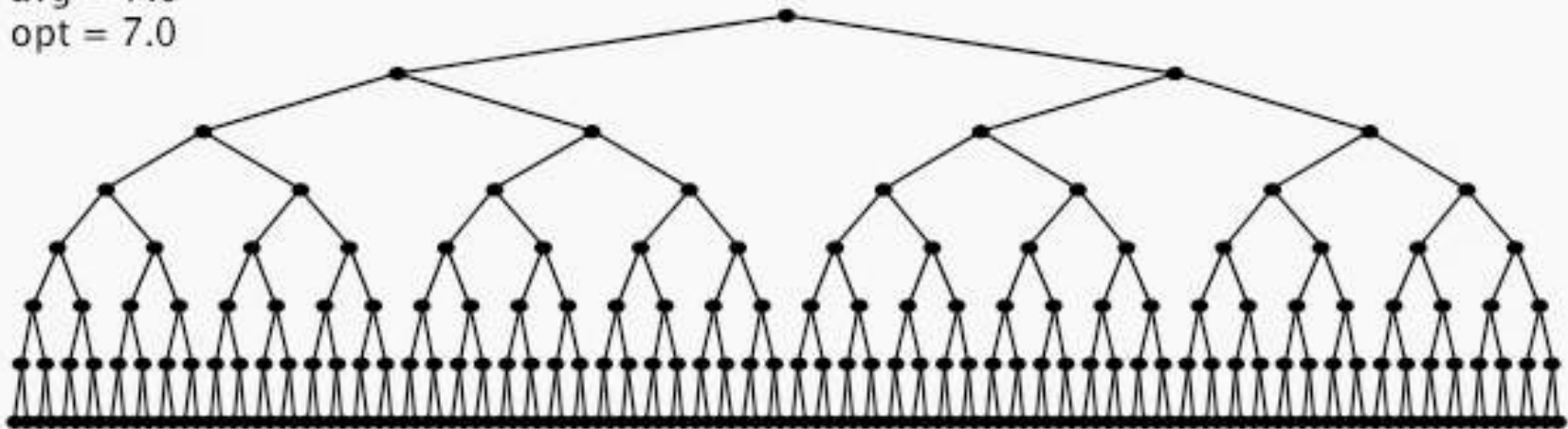
← balance 4-node

← split 4-node

↑ only a few extra lines of code provides near-perfect balance

Insertion in a LLRB tree: visualization

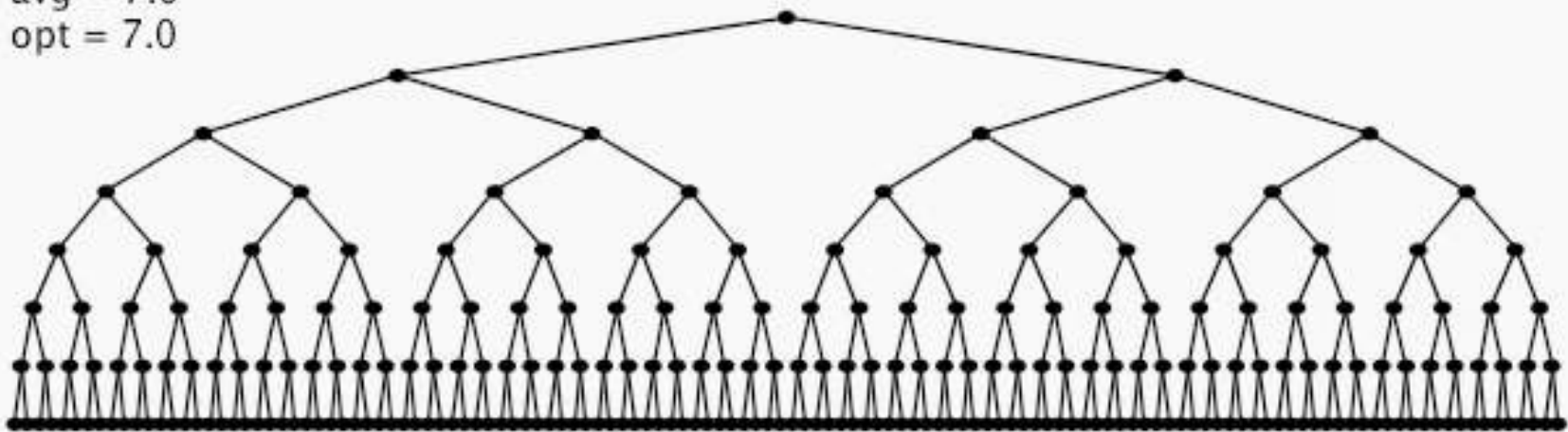
N = 255
max = 8
avg = 7.0
opt = 7.0



255 insertions in ascending order

Insertion in a LLRB tree: visualization

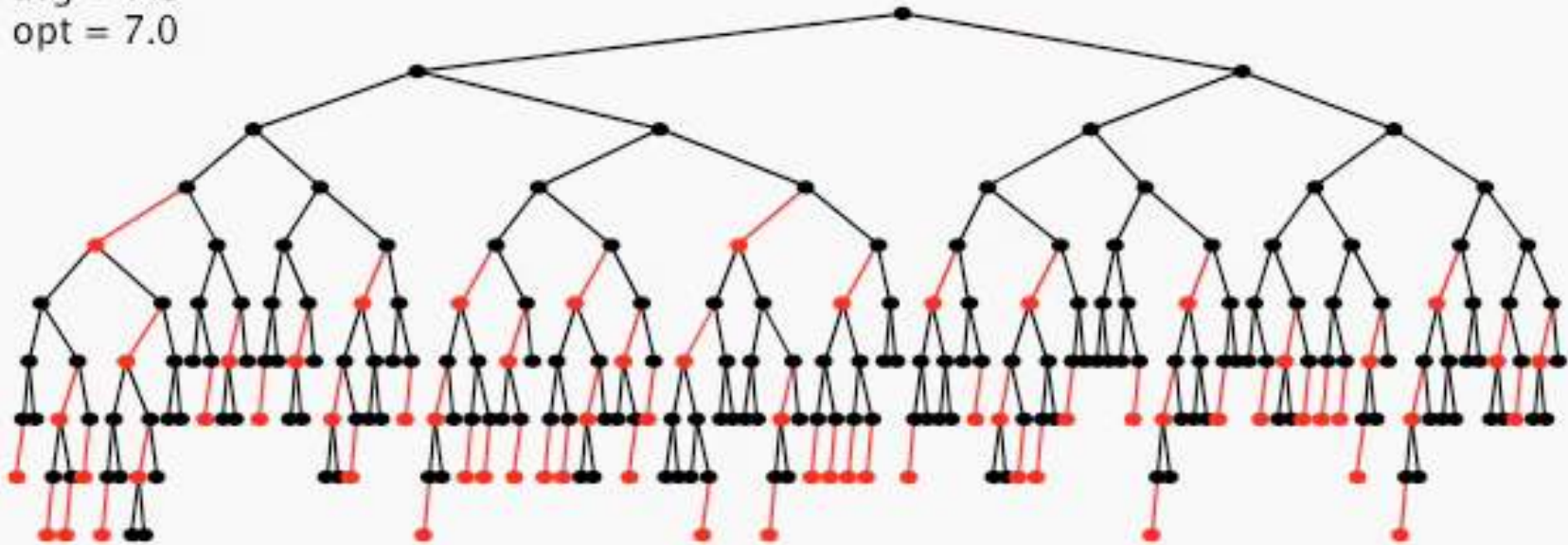
N = 255
max = 8
avg = 7.0
opt = 7.0



255 insertions in descending order

Insertion in a LLRB tree: visualization

N = 255
max = 10
avg = 7.3
opt = 7.0



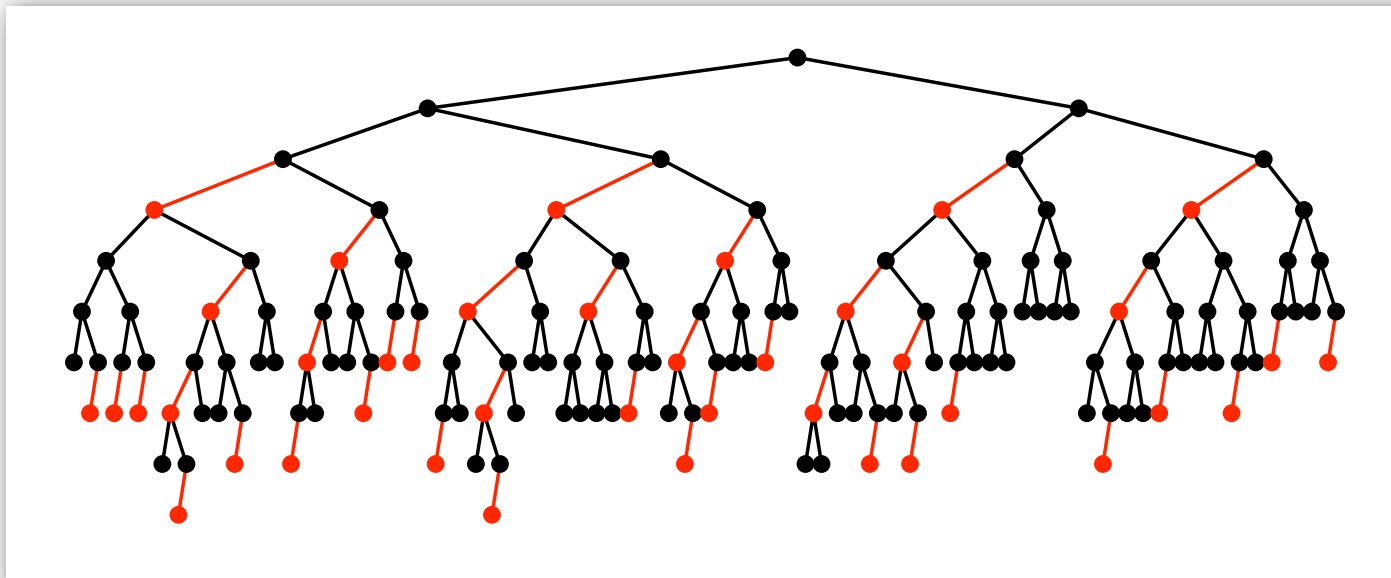
255 random insertions

Balance in LLRB trees

Proposition. Height of tree is $\leq 2 \lg N$ in the worst case.

Pf.

- Every path from root to null link has same number of black links.
- Never two red links in-a-row.



Property. Height of tree is $\sim 1.00 \lg N$ in typical applications.

ST implementations: summary

implementation	worst-case cost (after N inserts)			average case (after N random inserts)			ordered iteration?	key interface
	search	insert	delete	search hit	insert	delete		
sequential search (unordered 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	1.39 lg N	1.39 lg N	?	yes	compareTo()
2-3 tree	c lg N	c lg N	c lg N	c lg N	c lg N	c lg N	yes	compareTo()
red-black BST	2 lg N	2 lg N	2 lg N	1.00 lg N *	1.00 lg N *	1.00 lg N *	yes	compareTo()

* exact value of coefficient unknown but extremely close to 1

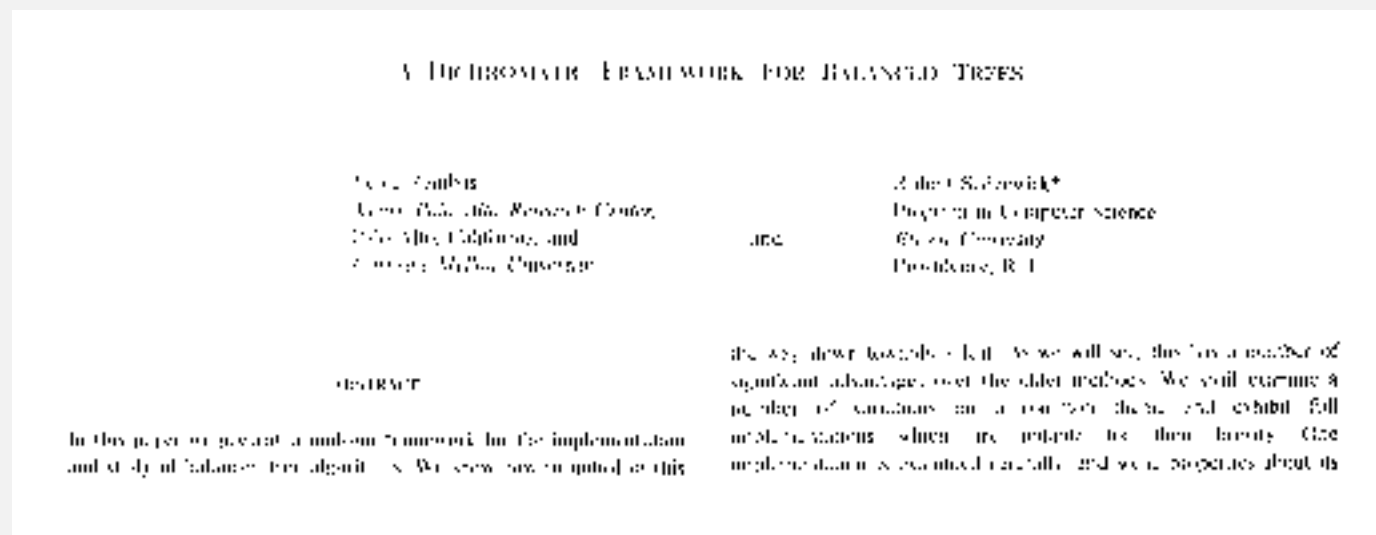
War story: why red-black?

Xerox PARC innovations. [1970s]

- Alto.
- GUI.
- Ethernet.
- Smalltalk.
- InterPress.
- Laser printing.
- Bitmapped display.
- WYSIWYG text editor.
- ...



Xerox Alto



War story: red-black BSTs

Telephone company contracted with database provider to build real-time database to store customer information.

Database implementation.

- Red-black BST search and insert; Hibbard deletion.
- Exceeding height limit of 80 triggered error-recovery process.

allows for up to 2^{40} keys

Extended telephone service outage.

Hibbard deletion
was the problem

- Main cause = height bounded exceeded!
- Telephone company sues database provider.
- Legal testimony:

“ If implemented properly, the height of a red-black BST with N keys is at most $2 \lg N$. ” — expert witness





3.3 BALANCED SEARCH TREES

- ▶ *2-3 search trees*
- ▶ *red-black BSTs*
- ▶ *B-trees*



3.3 BALANCED SEARCH TREES

- ▶ *2-3 search trees*
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File system model

Page. Contiguous block of data (e.g., a file or 4,096-byte chunk).

Probe. First access to a page (e.g., from disk to memory).



slow



fast

Property. Time required for a probe is much larger than time to access data within a page.

Cost model. Number of probes.

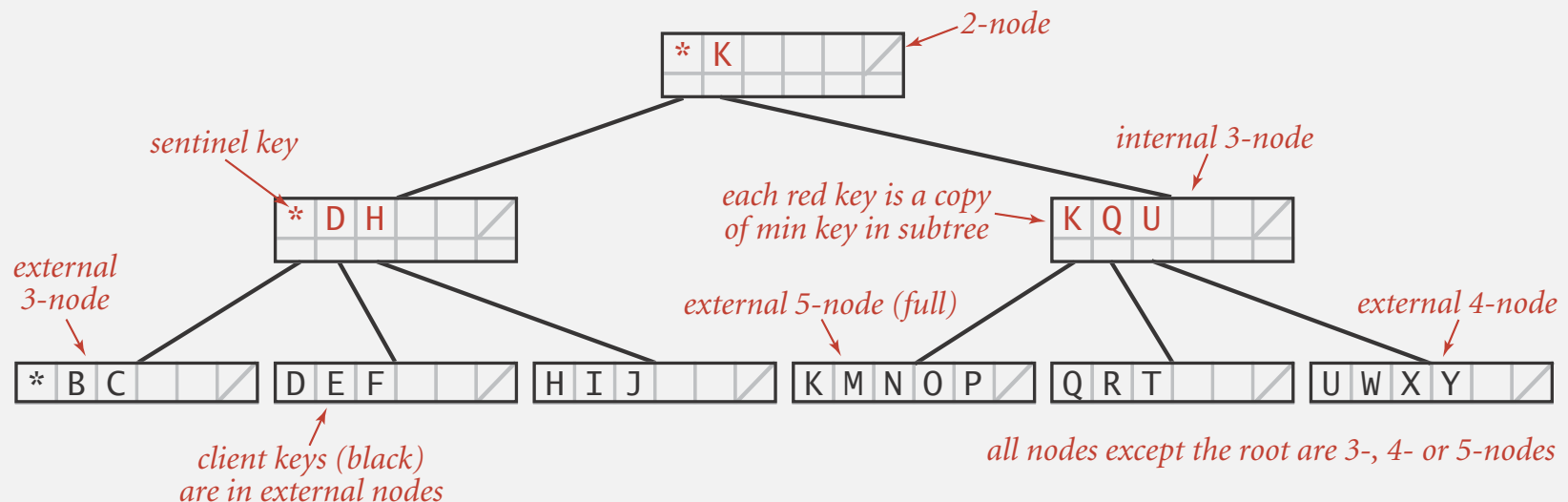
Goal. Access data using minimum number of probes.

B-trees (Bayer-McCreight, 1972)

B-tree. Generalize 2-3 trees by allowing up to $M - 1$ key-link pairs per node.

- At least 2 key-link pairs at root.
- At least $M / 2$ key-link pairs in other nodes.
- External nodes contain client keys.
- Internal nodes contain copies of keys to guide search.

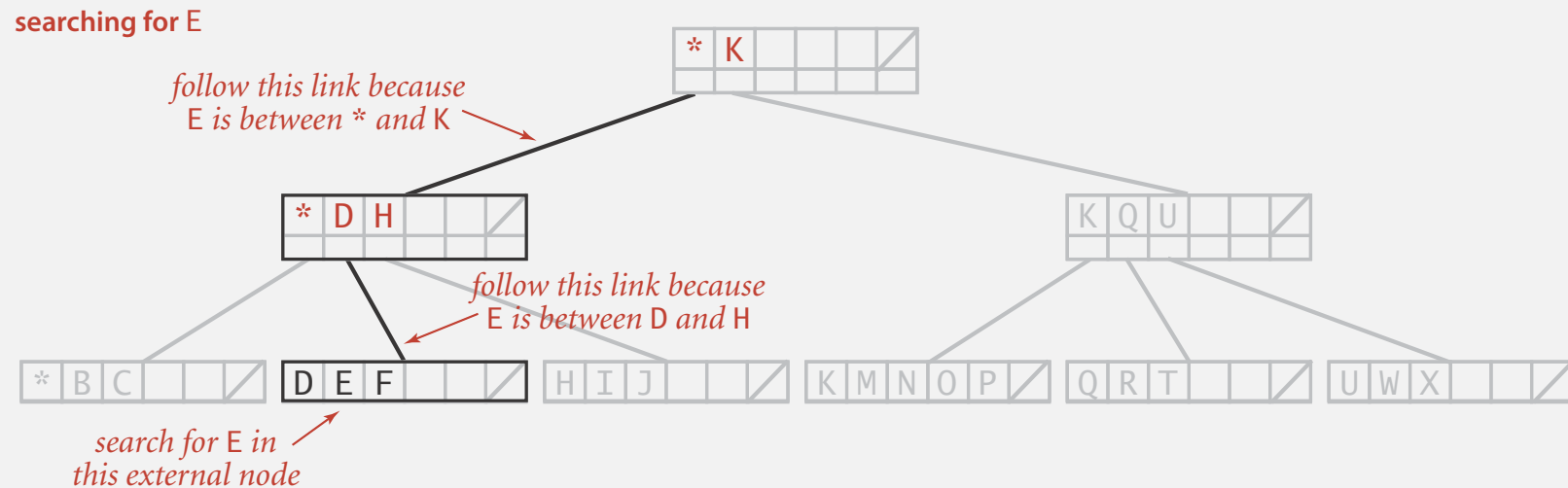
choose M as large as possible so that M links fit in a page, e.g., $M = 1024$



Anatomy of a B-tree set ($M = 6$)

Searching in a B-tree

- Start at root.
- Find interval for search key and take corresponding link.
- Search terminates in external node.

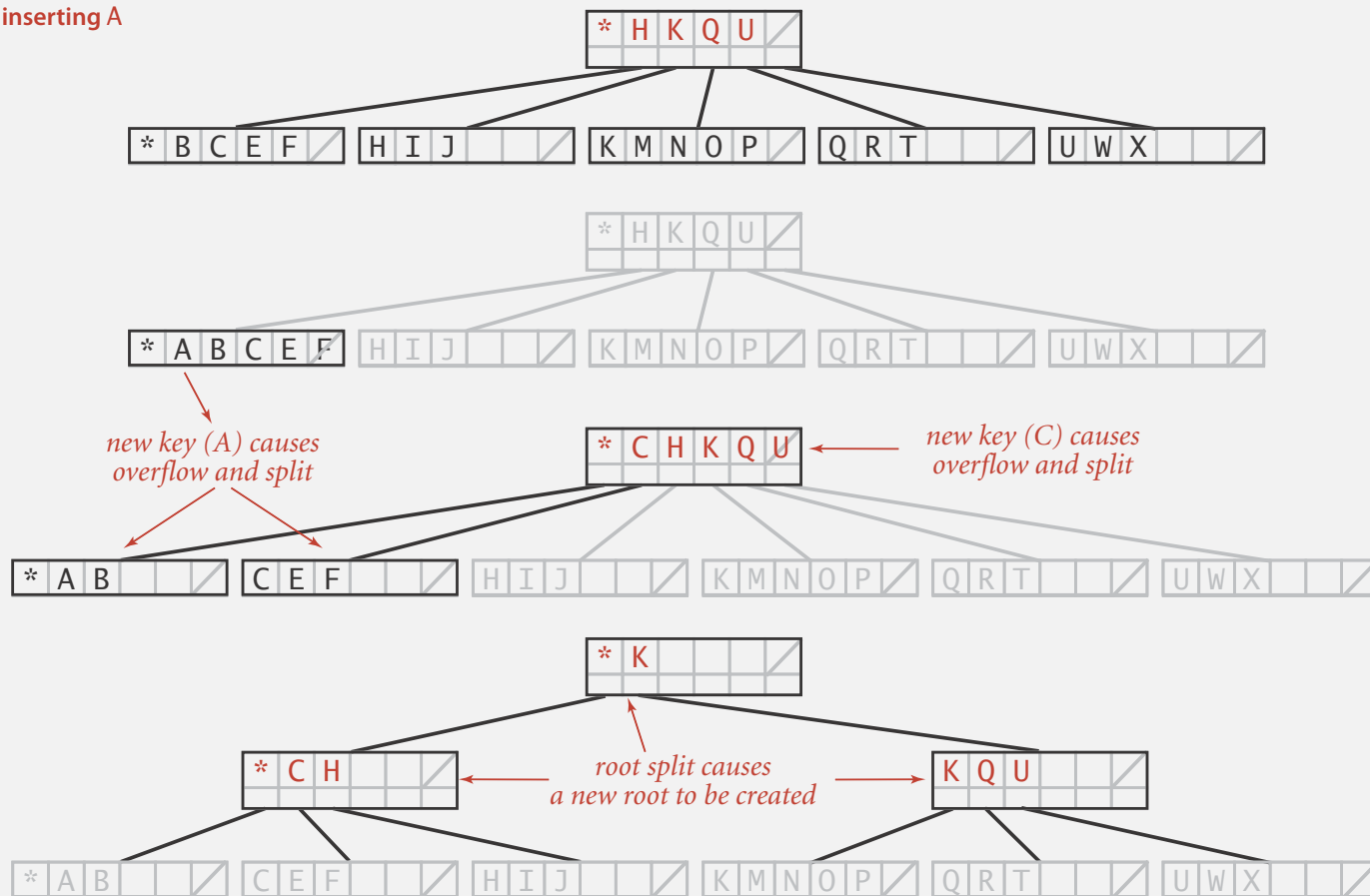


Searching in a B-tree set ($M = 6$)

Insertion in a B-tree

- Search for new key.
- Insert at bottom.
- Split nodes with M key-link pairs on the way up the tree.

inserting A

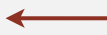


Inserting a new key into a B-tree set

Balance in B-tree

Proposition. A search or an insertion in a B-tree of order M with N keys requires between $\log_{M-1} N$ and $\log_{M/2} N$ probes.

Pf. All internal nodes (besides root) have between $M / 2$ and $M - 1$ links.

In practice. Number of probes is at most 4.  $M = 1024$; $N = 62$ billion
 $\log_{M/2} N \leq 4$

Optimization. Always keep root page in memory.

Building a large B tree



Balanced trees in the wild

Red-black trees are widely used as system symbol tables.

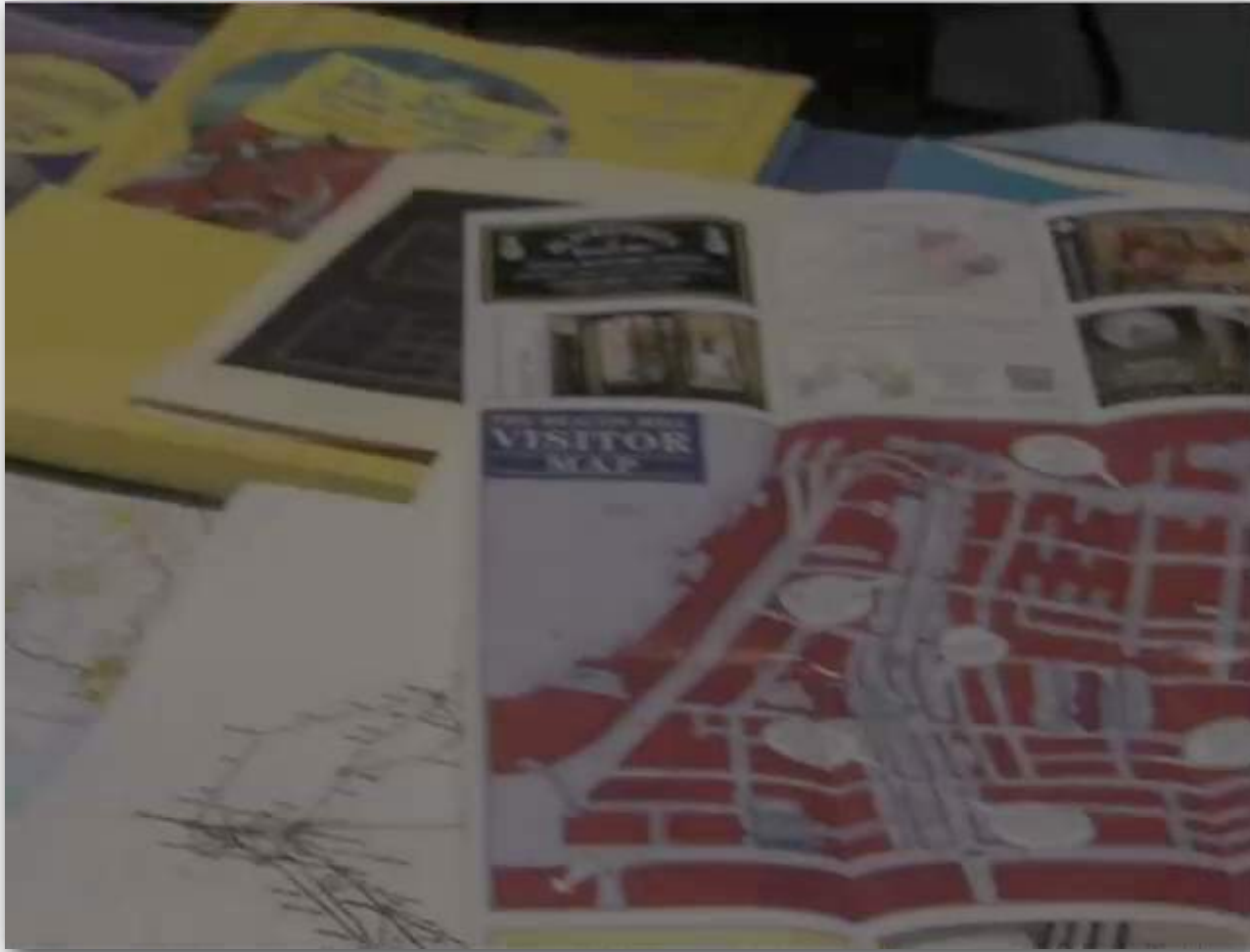
- Java: `java.util.TreeMap`, `java.util.TreeSet`.
- C++ STL: `map`, `multimap`, `multiset`.
- Linux kernel: completely fair scheduler, `linux/rbtree.h`.
- Emacs: conservative stack scanning.

B-tree variants. B+ tree, B*tree, B# tree, ...

B-trees (and variants) are widely used for file systems and databases.

- Windows: NTFS.
- Mac: HFS, HFS+.
- Linux: ReiserFS, XFS, Ext3FS, JFS.
- Databases: ORACLE, DB2, INGRES, SQL, PostgreSQL.

Red-black BSTs in the wild



*Common sense. Sixth sense.
Together they're the
FBI's newest team.*

Red-black BSTs in the wild

ACT FOUR

FADE IN:

48 INT. FBI HQ - NIGHT

48

Antonio is at THE COMPUTER as Jess explains herself to Nicole and Pollock. The CONFERENCE TABLE is covered with OPEN REFERENCE BOOKS, TOURIST GUIDES, MAPS and REAMS OF PRINTOUTS.

JESS

It was the red door again.

POLLOCK

I thought the red door was the storage container.

JESS

But it wasn't red anymore. It was black.

ANTONIO

So red turning to black means... what?

POLLOCK

Budget deficits? Red ink, black ink?

NICOLE

Yes. I'm sure that's what it is. But maybe we should come up with a couple other options, just in case.

Antonio refers to his COMPUTER SCREEN, which is filled with mathematical equations.

ANTONIO

It could be an algorithm from a binary search tree. A red-black tree tracks every simple path from a node to a descendant leaf with the same number of black nodes.

JESS

Does that help you with girls?



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<http://algs4.cs.princeton.edu>

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