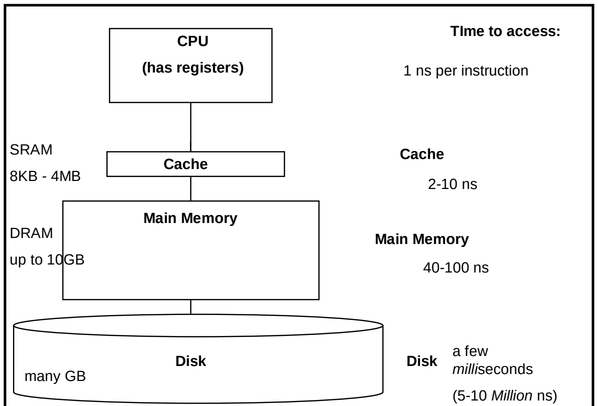
B-Trees
(4.7 in Weiss)

CSE 373
Data Structures & Algorithms
Ruth Anderson

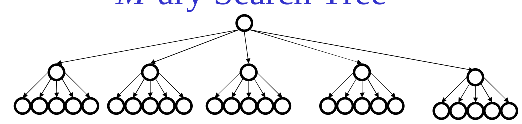
Trees so far

- BST

- AVL



M-ary Search Tree



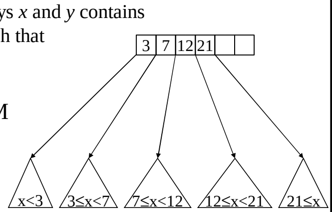
- Maximum branching factor of ***M***
- Complete tree has height =

\# disk accesses for *find*:

Runtime of *find*:

Solution: B-Trees

- specialized *M*-ary search trees
- Each **node** has (up to) M-1 keys:
  - subtree between two keys *x* and *y* contains leaves with *values* *v* such that $x \le v < y$



- Pick branching factor M such that each node takes one full {*page, block*} of memory

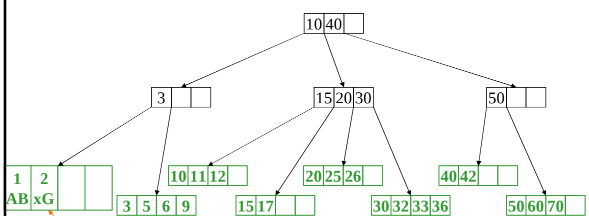
B-Trees

What makes them disk-friendly?

1. **Many keys stored in a node**
   - All brought to memory/cache in one access!
2. Internal nodes contain *only* keys;
   Only leaf nodes contain keys and actual *data*
   - The tree structure can be loaded into memory irrespective of data object size
   - Data actually resides in disk

B-Tree: Example

B-Tree with **M = 4** (# **pointers** in internal node)
and **L = 4** (# **data items** in **L**eaf)



Data objects, that I'll ignore in slides

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Note: All leaves at the same depth!

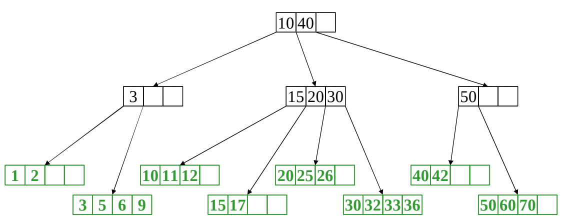
B-Tree Properties ‡

– Data is stored at the leaves
– All leaves are at the same depth and contain between $\lceil L/2 \rceil$ and L data items
– Internal nodes store up to $M-1$ keys
– Internal nodes have between $\lceil M/2 \rceil$ and M children
– Root (special case) has between 2 and M children (or root could be a leaf)

5/29/09 ‡These are technically B+-Trees 8

Example, Again

B-Tree with **M = 4**
and **L = 4**



5/29/09 (Only showing keys, but leaves also have data!) 9

B-trees vs. AVL trees

Suppose we have 100 million items (100,000,000):

- Depth of AVL Tree
- Depth of B+ Tree with M = 128, L = 64

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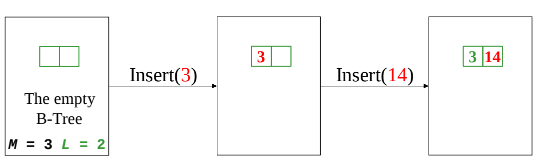
Building a B-Tree



Now, Insert(1)?

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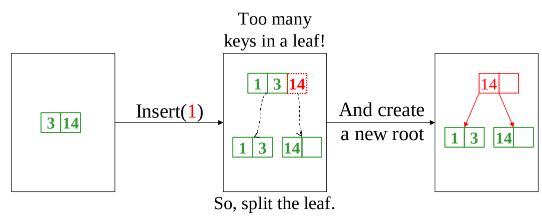
M = 3 L = 2

Splitting the Root



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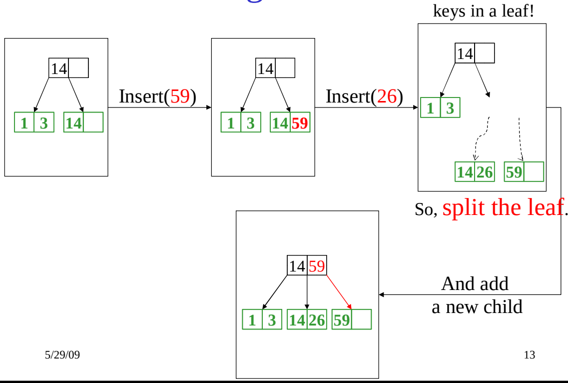
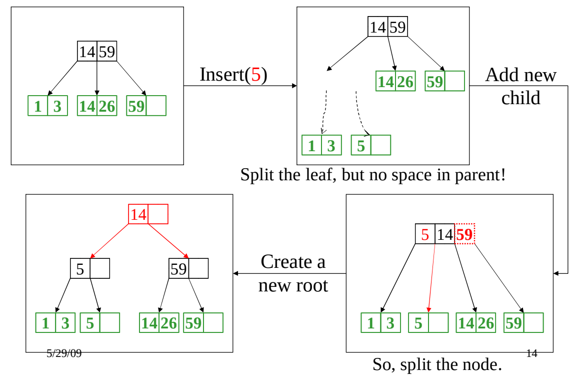
M = 3 *L* = 2

Overflowing leaves



M = 3 *L* = 2

Propagating Splits



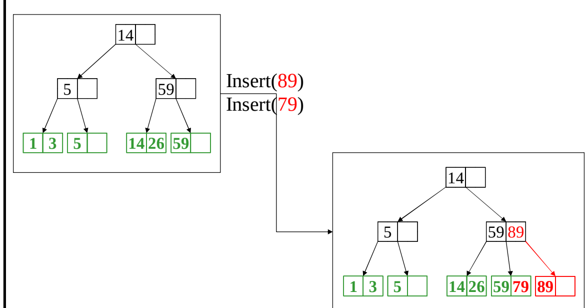
Insertion Algorithm

1. Insert the key in its leaf
2. If the leaf ends up with L+1 items, **overflow**!
   - Split the leaf into two nodes:
     - original with $\lceil (L+1)/2 \rceil$ items
     - new one with $\lfloor (L+1)/2 \rfloor$ items
   - Add the new child to the parent
   - If the parent ends up with ***M*+1** items, **overflow**!
3. If an internal node ends up with M+1 items, **overflow**!
   - Split the node into two nodes:
     - original with $\lceil (M+1)/2 \rceil$ items
     - new one with $\lfloor (M+1)/2 \rfloor$ items
   - Add the new child to the parent
   - If the parent ends up with ***M*+1** items, **overflow**!
4. Split an overflowed root in two and hang the new nodes under a new root

This makes the tree deeper!

M = 3 *L* = 2

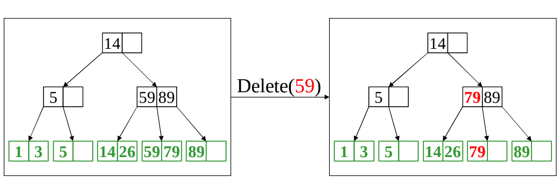
After More Routine Inserts



M = 3 *L* = 2

Deletion

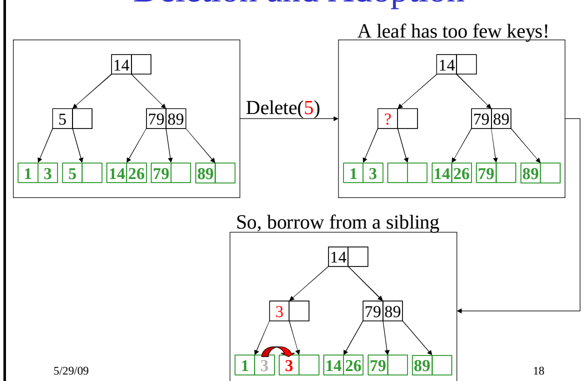
1. Delete item from leaf
2. Update keys of ancestors if necessary



What could go wrong?

M = 3 *L* = 2

Deletion and Adoption



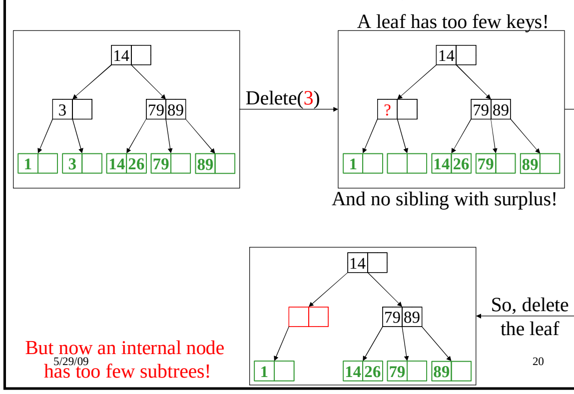
Does Adoption Always Work?

- What if the sibling doesn't have enough for you to borrow from?

  e.g. you have ⌈L/2⌉-1 and sibling has ⌈L/2⌉?

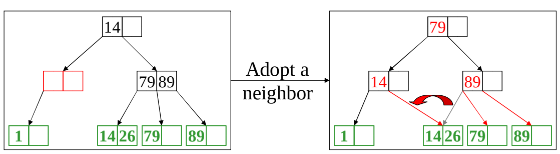
M = 3 *L* = 2

Deletion and Merging



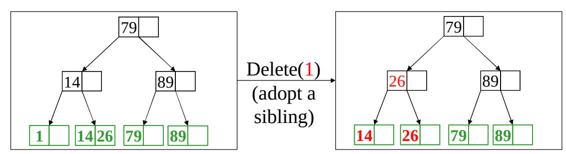
M = 3 *L* = 2

Deletion with Propagation (More Adoption)



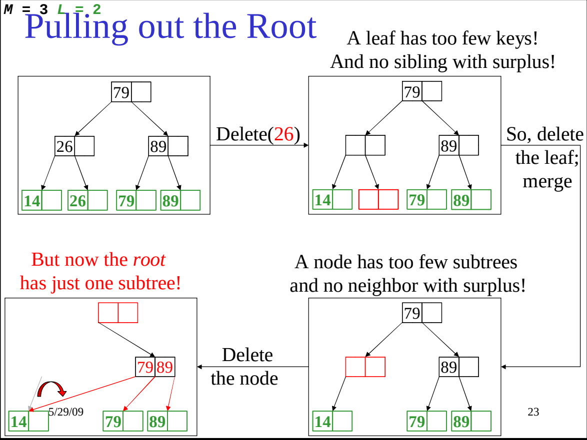
M = 3 *L* = 2

A Bit More Adoption



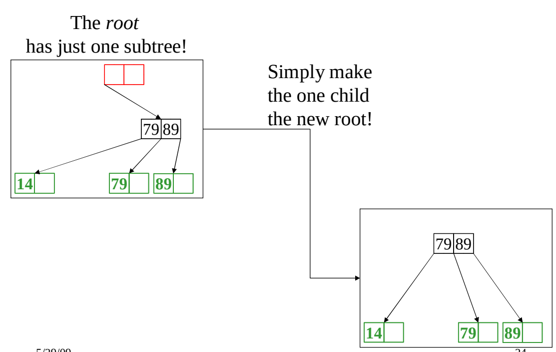
M = 3 *L* = 2

Pulling out the Root



M = 3 *L* = 2

Pulling out the Root (continued)



Deletion Algorithm

1. Remove the key from its leaf
2. If the **leaf** ends up with fewer than $\lceil L/2 \rceil$ items, **underflow**!
   - Adopt data from a sibling; update the parent
   - If adopting won't work, delete node and merge with neighbor
   - If the parent ends up with fewer than $\lceil M/2 \rceil$ items, **underflow**!

Deletion Slide Two

3. If an **internal** node ends up with fewer than $\lceil M/2 \rceil$ items, **underflow**!
   - Adopt from a neighbor; update the parent
   - If adoption won't work, merge with neighbor
   - If the parent ends up with fewer than $\lceil M/2 \rceil$ items, **underflow**!
4. If the root ends up with only one child, make the child the new root of the tree

This reduces the height of the tree!

Thinking about B-Trees

- B-Tree **insertion** can cause (expensive) splitting and propagation
- B-Tree **deletion** can cause (cheap) adoption or (expensive) deletion, merging and propagation
- Propagation is rare if M and L are large *(Why?)*
- If $M = L = 128$, then a B-Tree of height 4 will store at least 30,000,000 items

Tree Names You Might Encounter

FYI:
- B-Trees with $M = 3$, $L = x$ are called **2-3 trees**
  - Nodes can have 2 or 3 pointers
- B-Trees with $M = 4$, $L = x$ are called **2-3-4 trees**
  - Nodes can have 2, 3, or 4 pointers