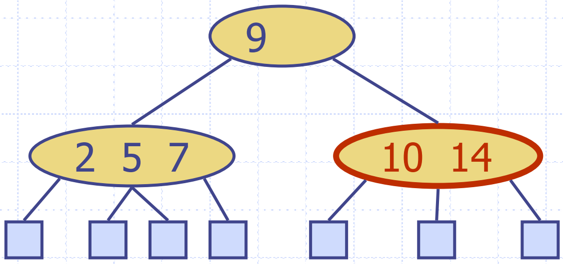
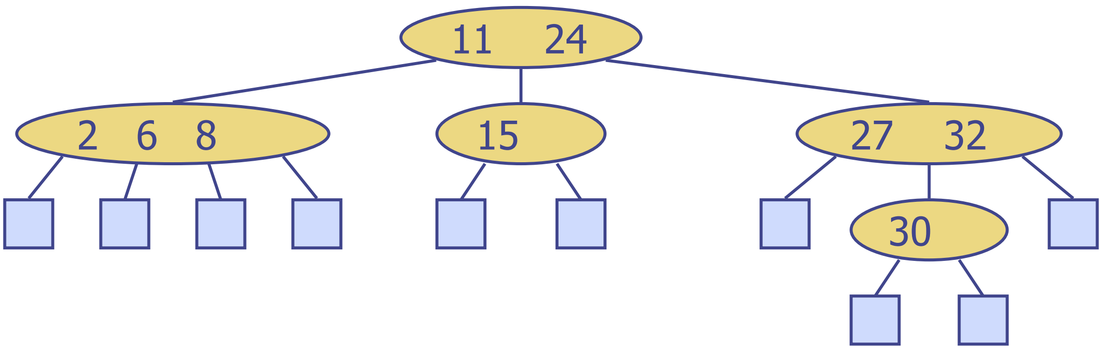
(2,4) Trees: Very Briefly



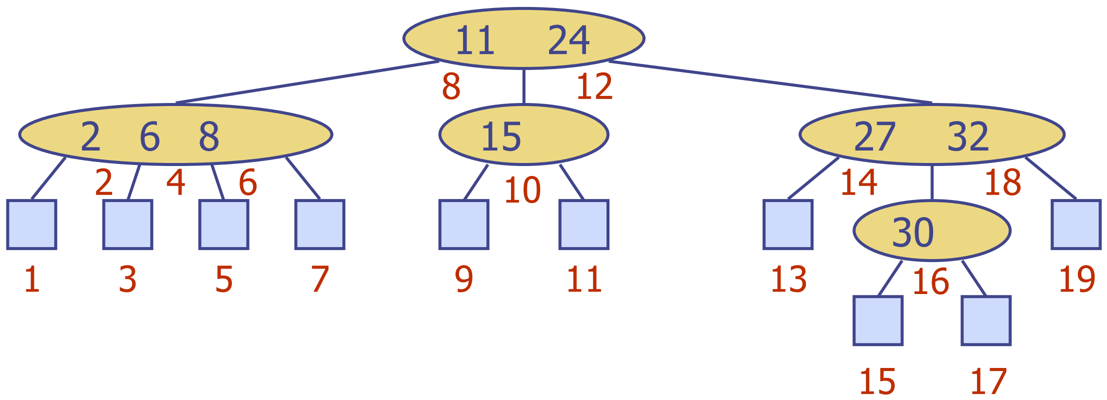
Multi-Way Search Tree

- A multi-way search tree is an ordered tree such that
  - Each internal node has at least two children and stores $d-1$ key-element items (k_i, o_i), where d is the number of children
  - For a node with children $v_1\ v_2\ \ldots\ v_d$ storing keys $k_1\ k_2\ \ldots\ k_{d-1}$
    - keys in the subtree of v_1 are less than k_1
    - keys in the subtree of v_i are between k_{i-1} and k_i $(i = 2, \ldots, d-1)$
    - keys in the subtree of v_d are greater than k_{d-1}
  - The leaves store no items and serve as placeholders



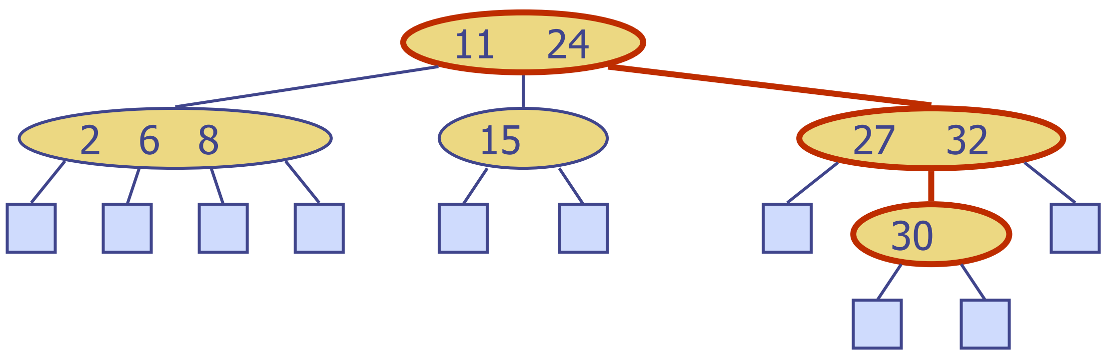
Multi-Way Inorder Traversal

- We can extend the notion of inorder traversal from binary trees to multi-way search trees
- Namely, we visit item (k_i, o_i) of node v between the recursive traversals of the subtrees of v rooted at children v_i and v_{i+1}
- An inorder traversal of a multi-way search tree visits the keys in increasing order



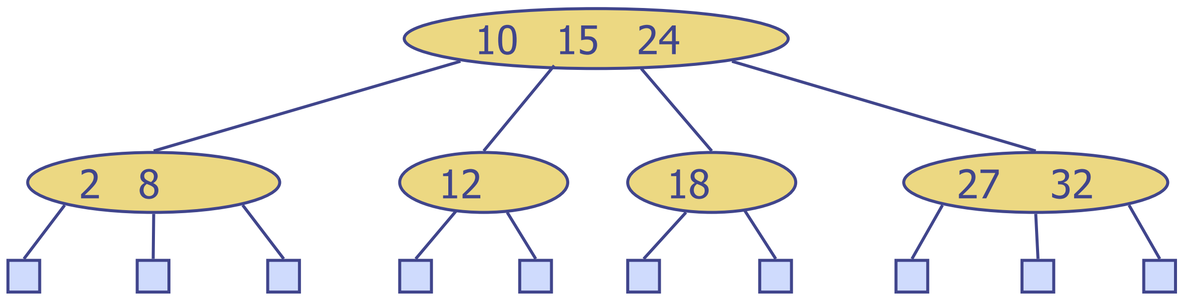
Multi-Way Searching

- Similar to search in a binary search tree
- A each internal node with children $v_1\ v_2\ \dots\ v_d$ and keys $k_1\ k_2\ \dots\ k_{d-1}$
  - $k = k_i\ (i = 1, \dots, d-1)$: the search terminates successfully
  - $k < k_1$: we continue the search in child v_1
  - $k_{i-1} < k < k_i\ (i = 2, \dots, d-1)$: we continue the search in child v_i
  - $k > k_{d-1}$: we continue the search in child v_d
- Reaching an external node terminates the search unsuccessfully
- Example: search for 30



(2,4) Trees

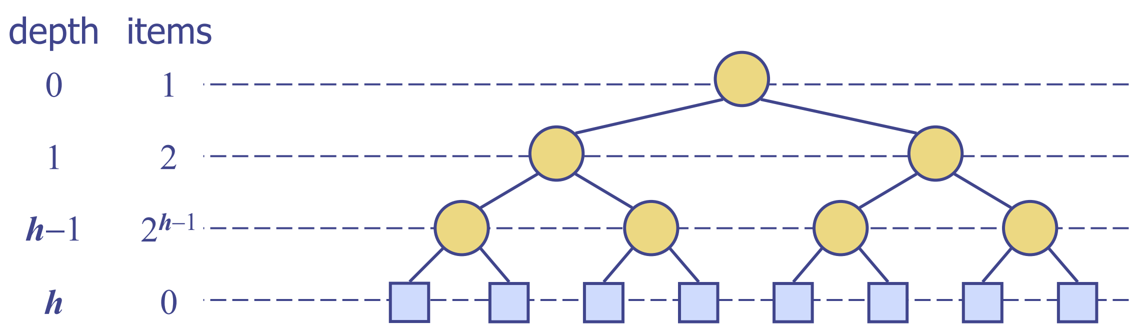
- A (2,4) tree (also called 2-4 tree or 2-3-4 tree) is a multi-way search with the following properties
  - Node-Size Property: every internal node has at most four children (i.e., three keys)
  - Depth Property: all the external nodes have the same depth
- Depending on the number of children, an internal node of a (2,4) tree is called a 2-node, 3-node or 4-node



- (Question) Why not like the "height-balancing property" of AVL trees?

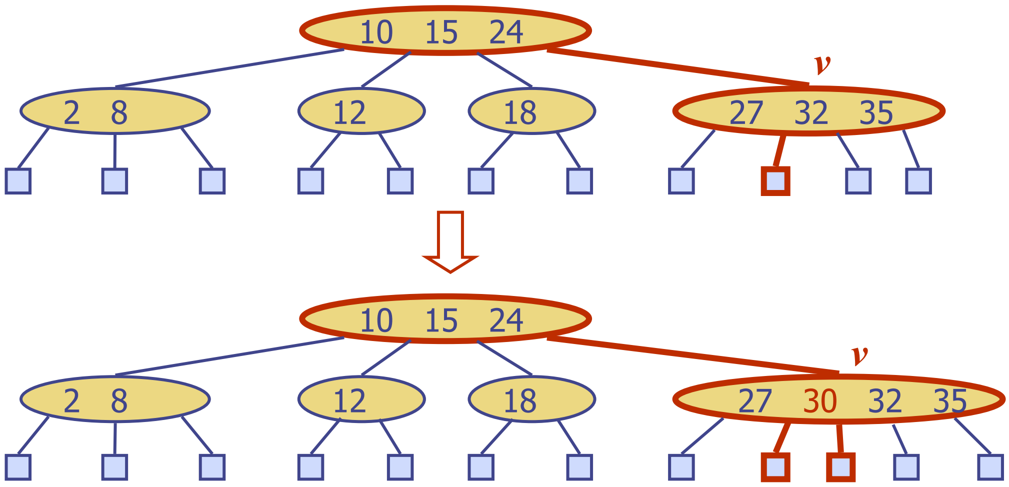
Height of a (2,4) Tree

- Theorem: A (2,4) tree storing n items has height $O(\log n)$
- Proof: Obvious ☺



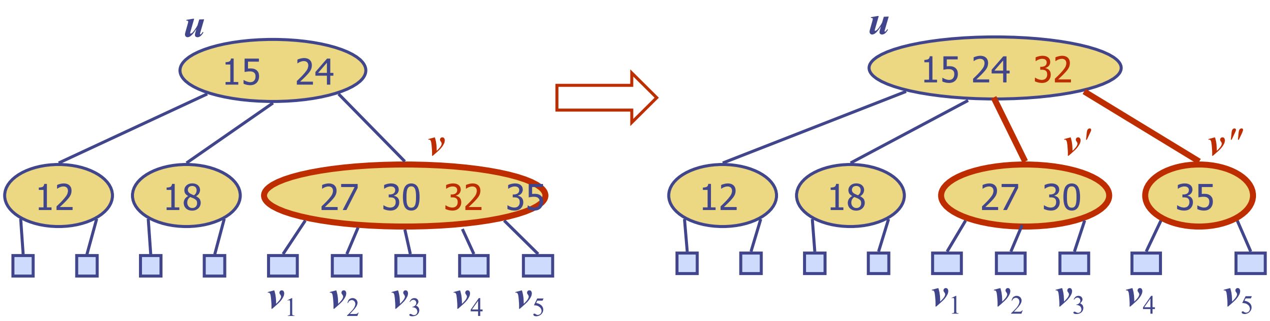
Insertion

- Insert a new item (k, o) at the parent v of the leaf reached by searching for k
  - We preserve the depth property but
  - We may cause an overflow (i.e., node v may become a 5-node)
- Example: inserting key 30 causes an overflow



Overflow and Split

- We handle an overflow at a 5-node v with a split operation:
  - let $v_1 \dots v_5$ be the children of v and $k_1 \dots k_4$ be the keys of v
  - node v is replaced by nodes v' and v''
    - v' is a 3-node with keys k_1 k_2 and children v_1 v_2 v_3
    - v'' is a 2-node with key k_4 and children v_4 v_5
  - key k_3 is inserted into the parent u of v (a new root may be created)
- The overflow may propagate to the parent node u



Analysis of Insertion

Algorithm ***put***(k, o)

1. We search for key $\boldsymbol{k}$ to locate the insertion node $\boldsymbol{v}$
2. We add the new entry $(\boldsymbol{k}, \boldsymbol{o})$ at node $\boldsymbol{v}$
3. **while** ***overflow***(v)

   if ***isRoot***(v)

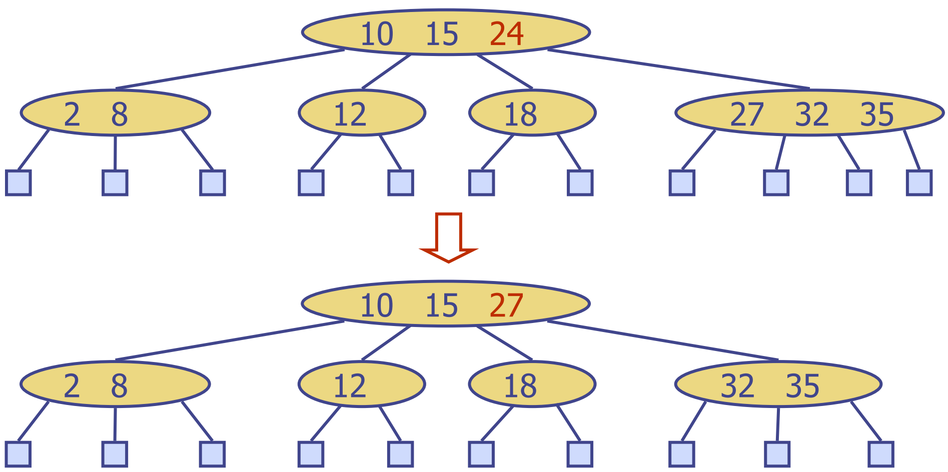
   create a new empty root above $\boldsymbol{v}$

   $v \leftarrow$ ***split***(v)

- Let $\boldsymbol{T}$ be a (2,4) tree with $\boldsymbol{n}$ items
  - Tree $\boldsymbol{T}$ has $\boldsymbol{O}(\log \boldsymbol{n})$ height
  - Step 1 takes $\boldsymbol{O}(\log \boldsymbol{n})$ time because we visit $\boldsymbol{O}(\log \boldsymbol{n})$ nodes
  - Step 2 takes $\boldsymbol{O}(1)$ time
  - Step 3 takes $\boldsymbol{O}(\log \boldsymbol{n})$ time because each split takes $\boldsymbol{O}(1)$ time and we perform $\boldsymbol{O}(\log \boldsymbol{n})$ splits
- Thus, an insertion in a (2,4) tree takes $\boldsymbol{O}(\log \boldsymbol{n})$ time

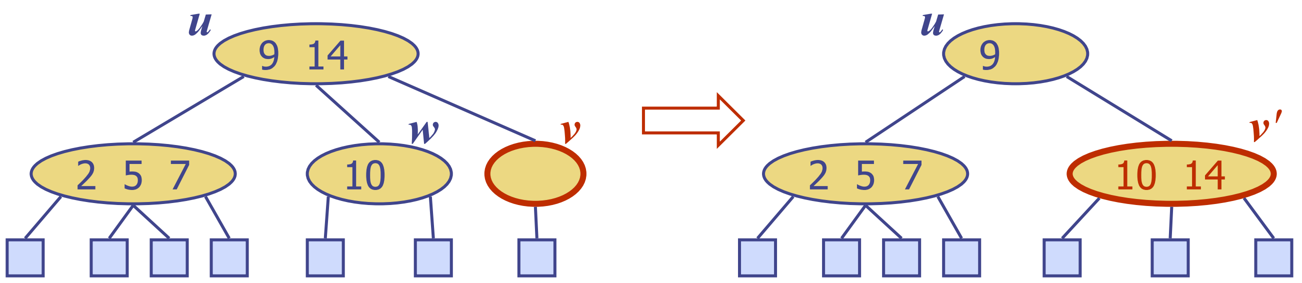
Deletion

- We reduce deletion of an entry to the case where the item is at the node with leaf children
- Otherwise, we replace the entry with its inorder successor (or, equivalently, with its inorder predecessor) and delete the latter entry
- Example: to delete key 24, we replace it with 27 (inorder successor)



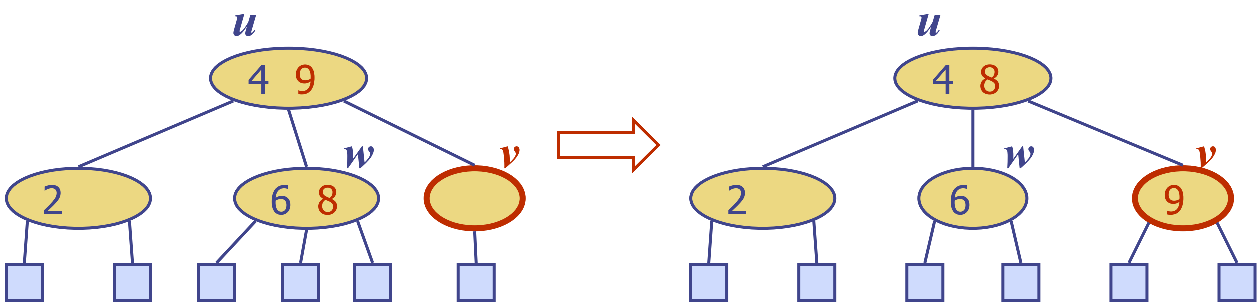
Underflow and Fusion

- Deleting an entry from a node v may cause an underflow, where node v becomes a 1-node with one child and no keys
- To handle an underflow at node v with parent u, we consider two cases
- Case 1: the adjacent siblings of v are 2-nodes
  - Fusion operation: we merge v with an adjacent sibling w and move an entry from u to the merged node v'
  - After a fusion, the underflow may propagate to the parent u



Underflow and Transfer

- Case 2: an adjacent sibling w of v is a 3-node or a 4-node
  - Transfer operation:
    1. we move a child of w to v
    2. we move an item from u to v
    3. we move an item from w to u
  - After a transfer, no underflow occurs



Analysis of Deletion

- Let T be a (2,4) tree with n items
  - Tree T has $O(\log n)$ height
- In a deletion operation
  - We visit $O(\log n)$ nodes to locate the node from which to delete the entry
  - We handle an underflow with a series of $O(\log n)$ fusions, followed by at most one transfer
  - Each fusion and transfer takes $O(1)$ time
- Thus, deleting an item from a (2,4) tree takes $O(\log n)$ time

Comparison of Map Implementations

	Find	Put	Erase	Notes
Hash Table	1 expected	1 expected	1 expected	○ no ordered map methods ○ simple to implement
Skip List	$\log n$ high prob.	$\log n$ high prob.	$\log n$ high prob.	○ randomized insertion ○ simple to implement
AVL and (2,4) Tree	$\log n$ worst-case	$\log n$ worst-case	$\log n$ worst-case	○ complex to implement

Questions?