Topic 7
Lecture 7d
2,4 Trees

CSCI 240

Data Structures and Algorithms

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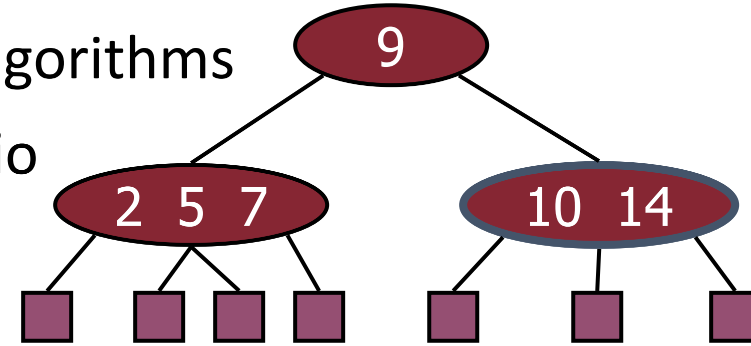
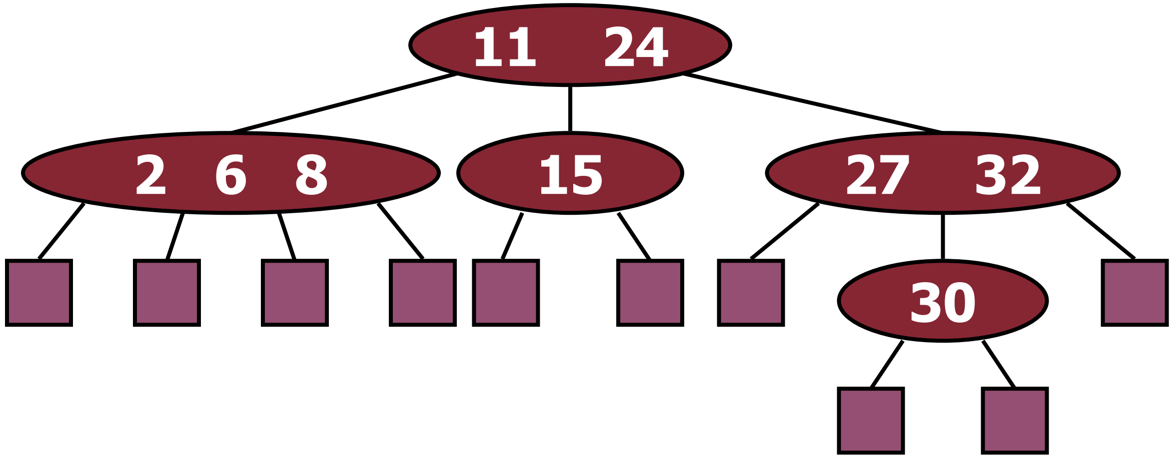


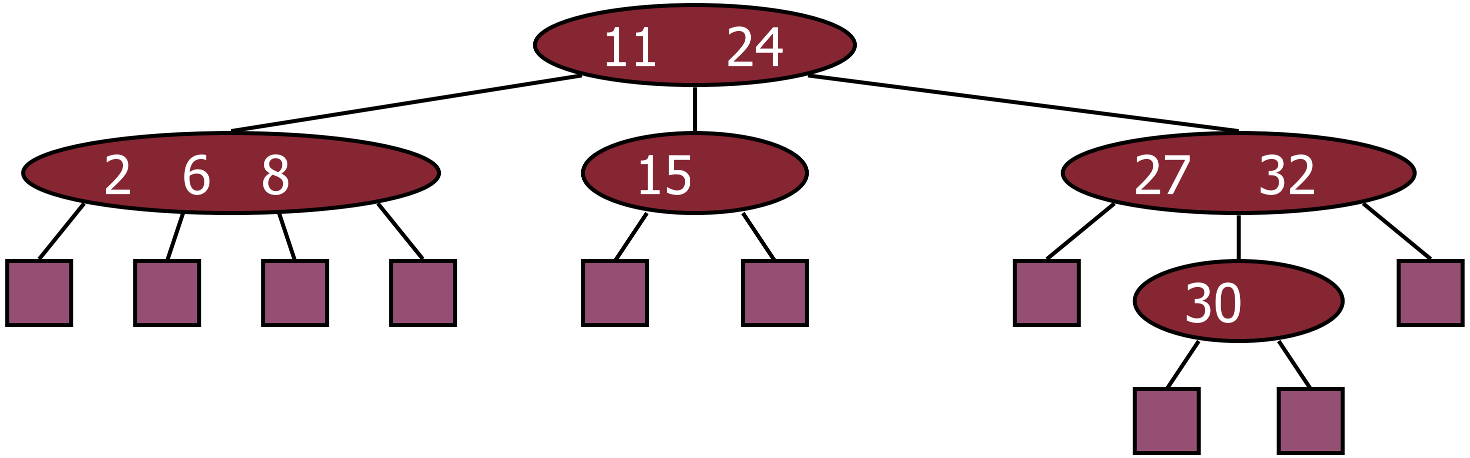
Multi-Way Search Tree

- 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 $v_1\ v_2\ \dots\ v_d$ storing keys $k_1\ k_2\ \dots\ k_{d-1}$
    - 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 $(i = 2, \dots, d - 1)$
    - keys in the subtree of v_d are greater than k_{d-1}
  - The leaves store no items and serve as placeholders



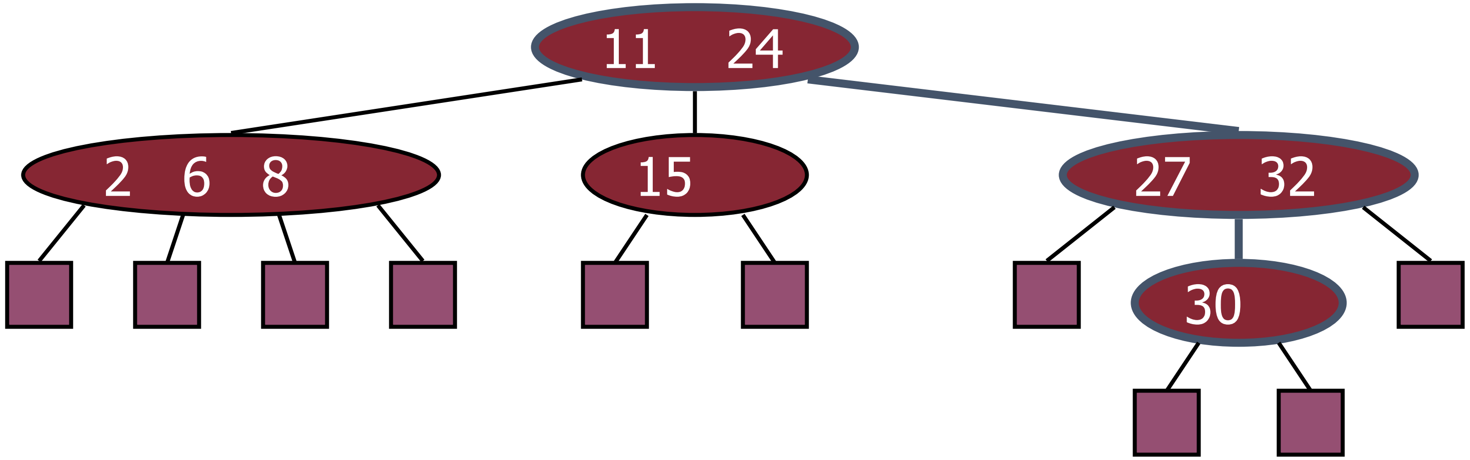
Multi-Way Inorder Traversal

- 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



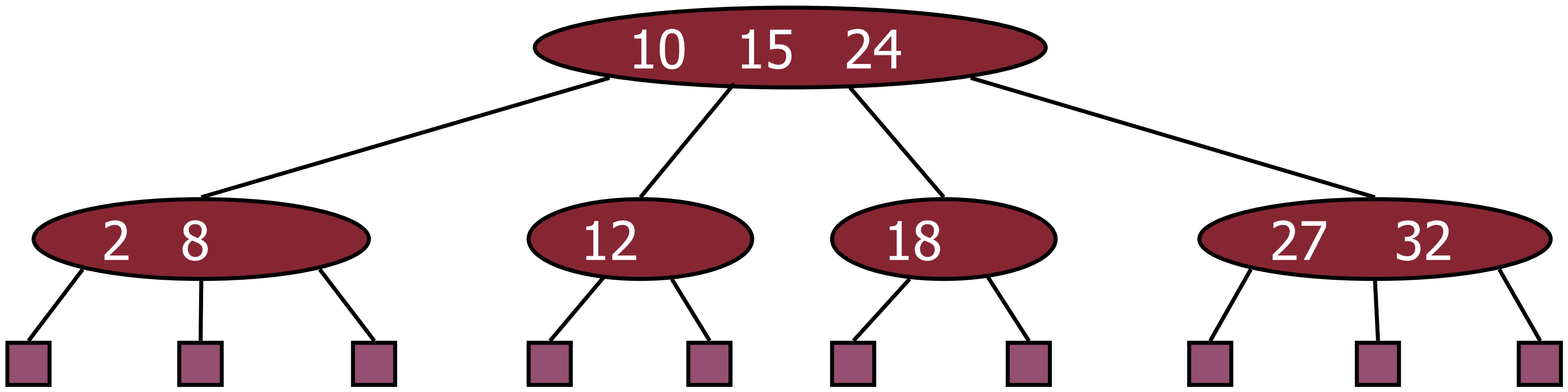
Multi-Way Searching

- Similar to search in a binary search tree
- A each internal node with children v_1 v_2 … v_d and keys k1 k2 … k_{d-1}
  - k = k_i (i = 1, …, d - 1): the search terminates successfully
  - k < k_1: we continue the search in child v1
  - ki-1 < k < k_i (i = 2, …, d - 1): we continue the search in child vi
  - k > k_{d-1}: we continue the search in child vd
- Reaching an external node terminates the search unsuccessfully
- Example: search for 30



(2,4) Trees

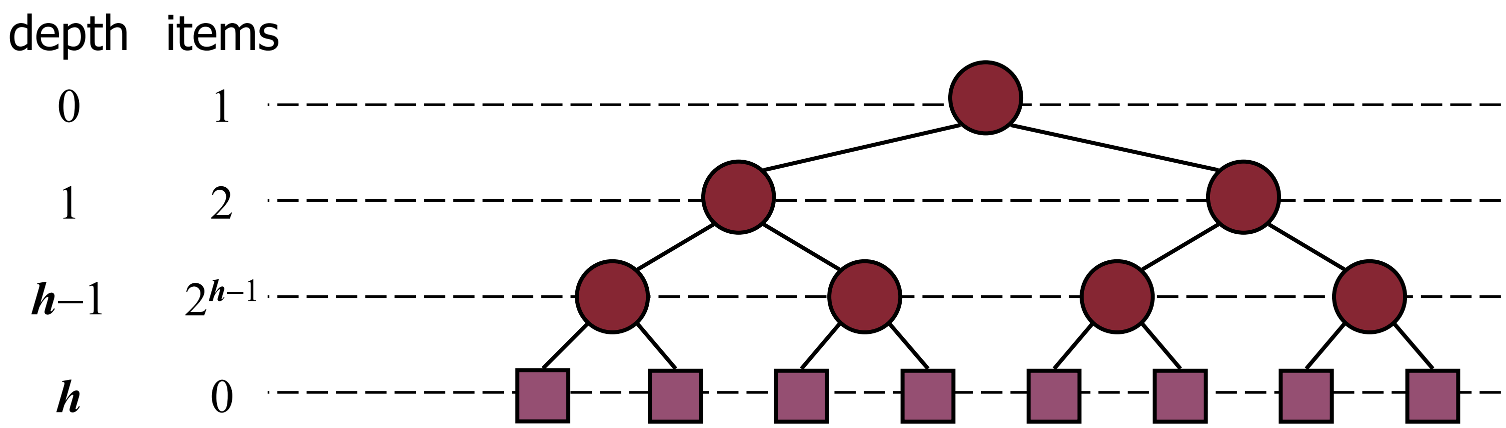
- A (2,4) tree (also called 2-4 tree or 2-3-4 tree) is a multi-way search with the following properties
  - Node-Size Property: every internal node has at most four children
  - Depth Property: all the external nodes have the same depth
- Depending on the number of children, an internal node of a (2,4)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



Height of a (2,4) Tree

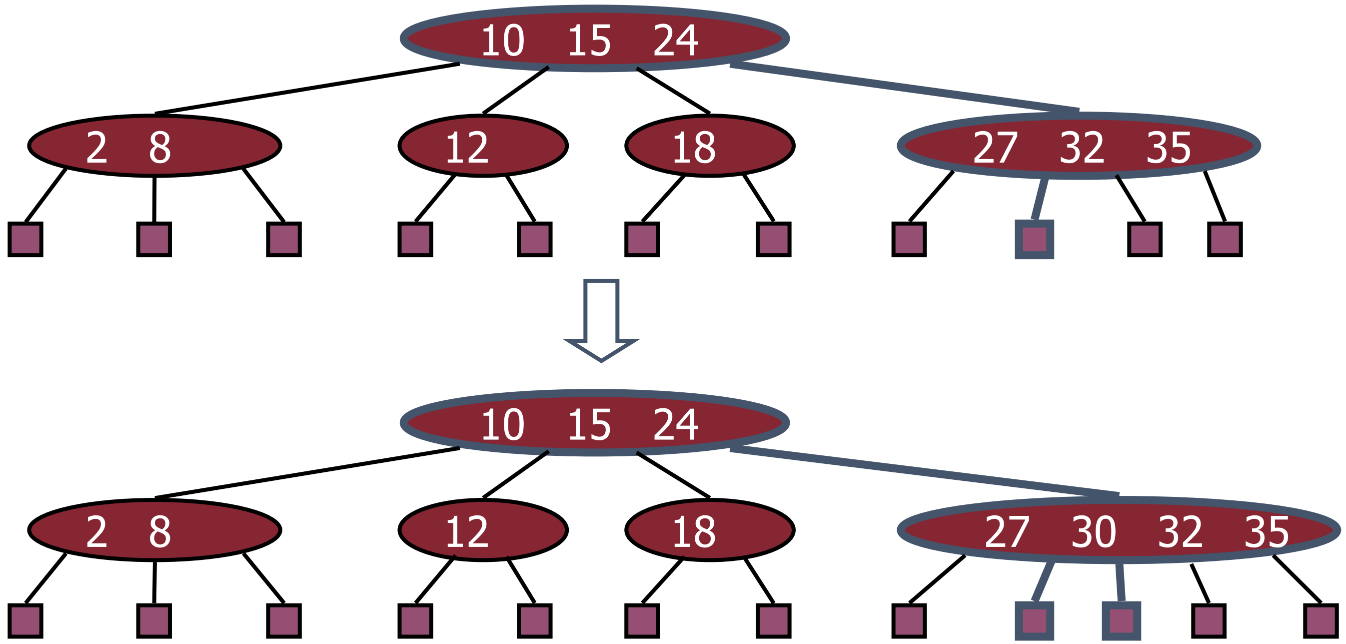
- Theorem: A (2,4) tree storing n items has height O(log n)
- Proof:
  - Let h be the height of a (2,4) tree with n items
  - Since there are at least 2i items at depth i = 0, … , h - 1 and no items at depth h, we have

    $n \geq 1 + 2 + 4 + \ldots + 2h\text{-}1 = 2h - 1$
  - Thus, $h \leq \log (n + 1)$
- Searching in a (2,4) tree with n items takes O(log n) time



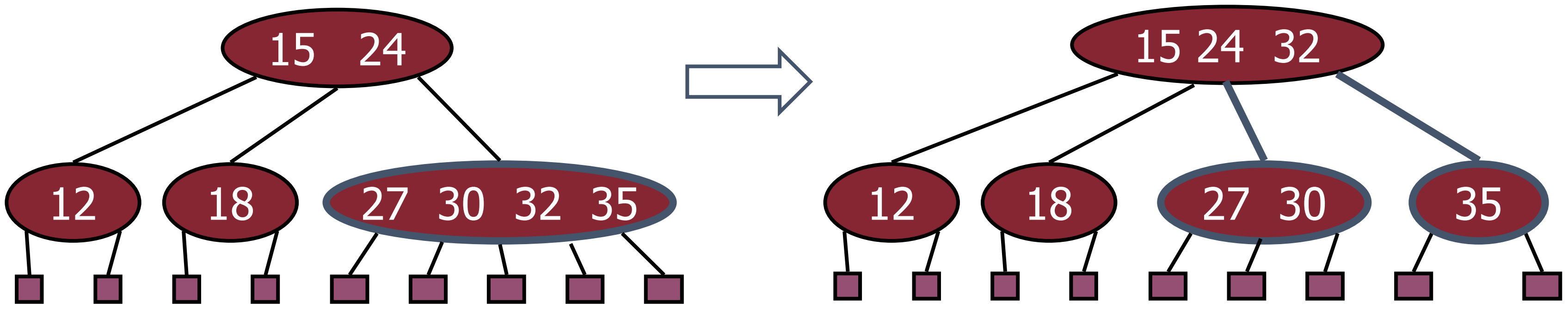
Insertion

- We 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 v1 … v5 be the children of v and k1 … k4 be the keys of v
  - node v is replaced nodes v' and v"
    - v' is a 3-node with keys k1 k2 and children v1 v2 v3
    - v" is a 2-node with key k4 and children v4 v5
  - key k3 is inserted into the parent u of v (a new root may be created)
- The overflow may propagate to the parent node u



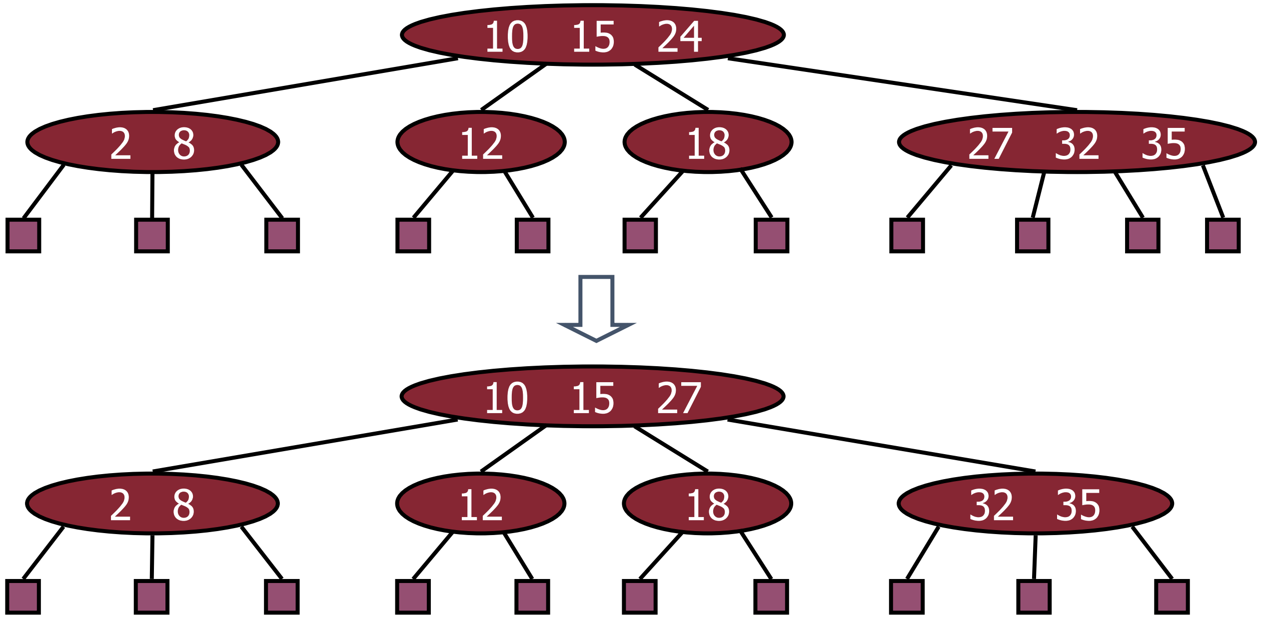
Analysis of Insertion

- Algorithm put(k, o)
- 1. We search for key k to locate the insertion node v
- 2. We add the new entry (k, o) at node v
- 3. while overflow(v)
  - if isRoot(v)
  - create a new empty root above v
  - v ← split(v)

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

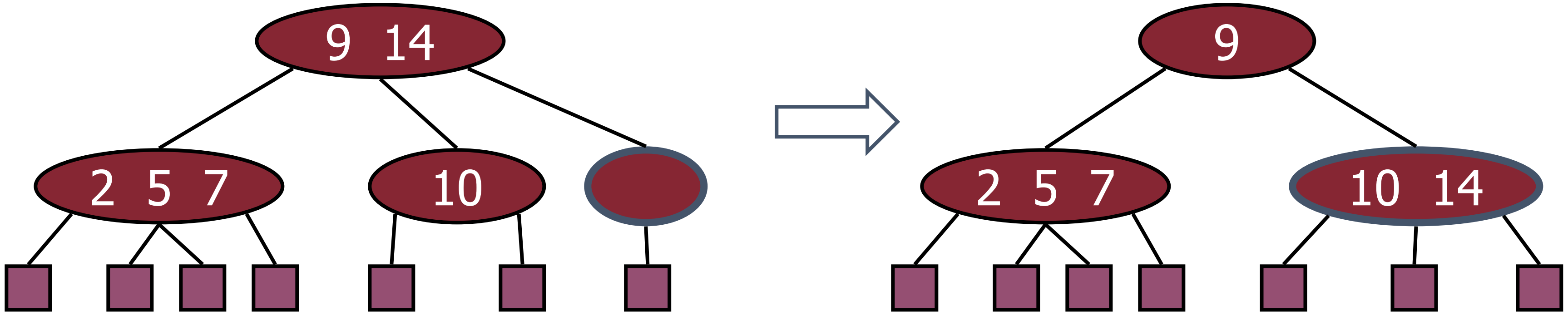
Deletion

- 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)



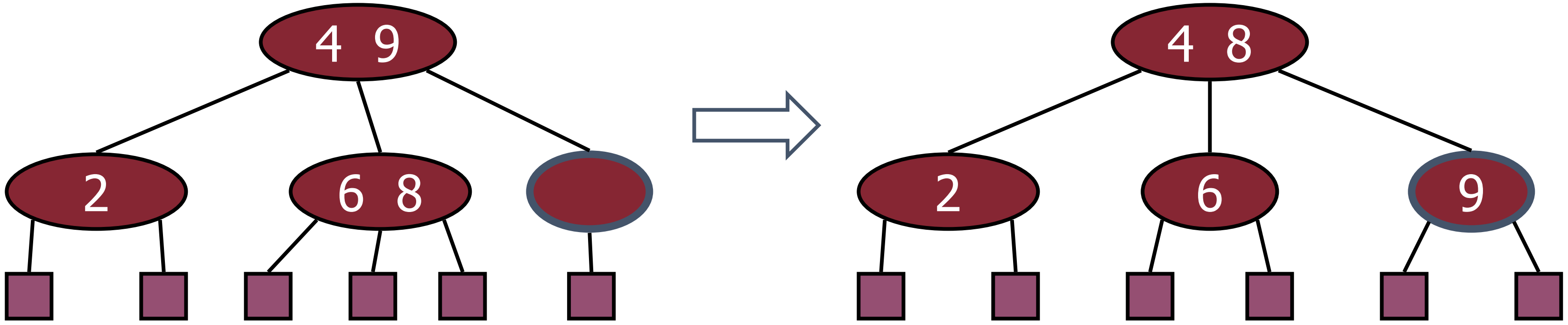
Underflow and Fusion

- 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

- To handle an underflow at node v with parent u, we consider two cases
- 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