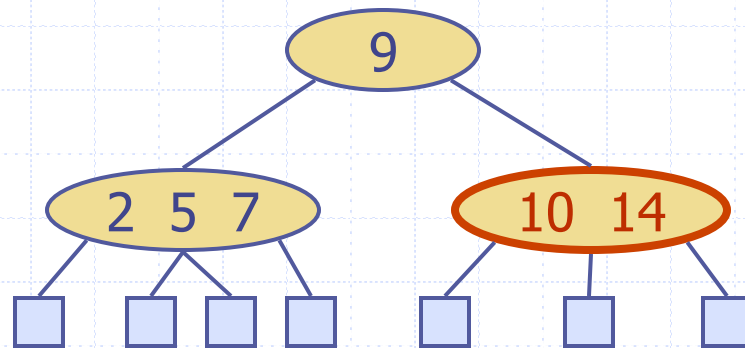
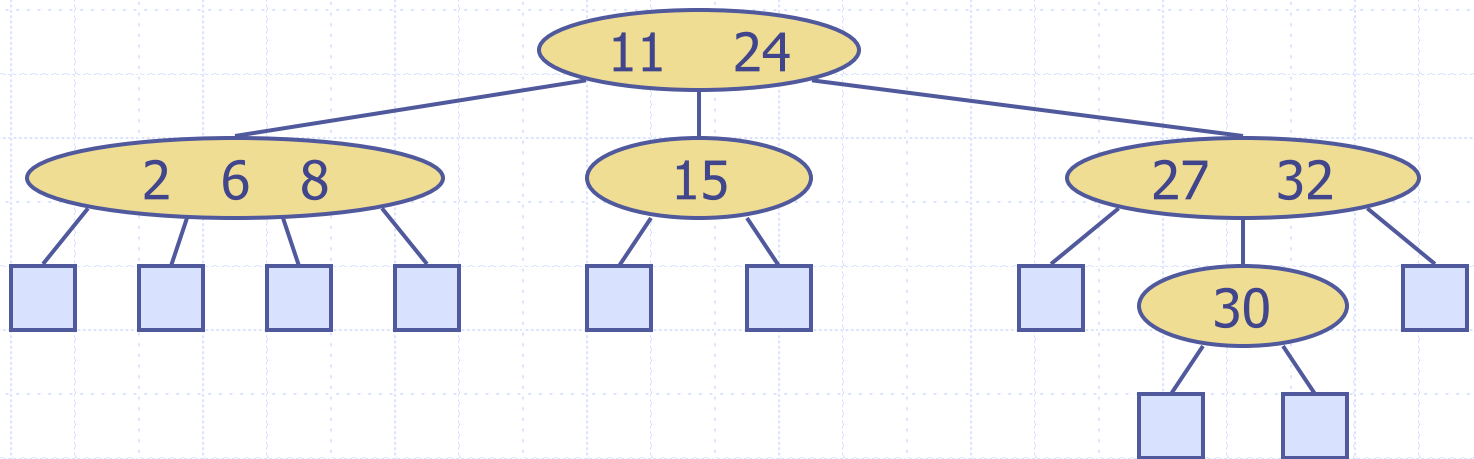


# (2,4) Trees



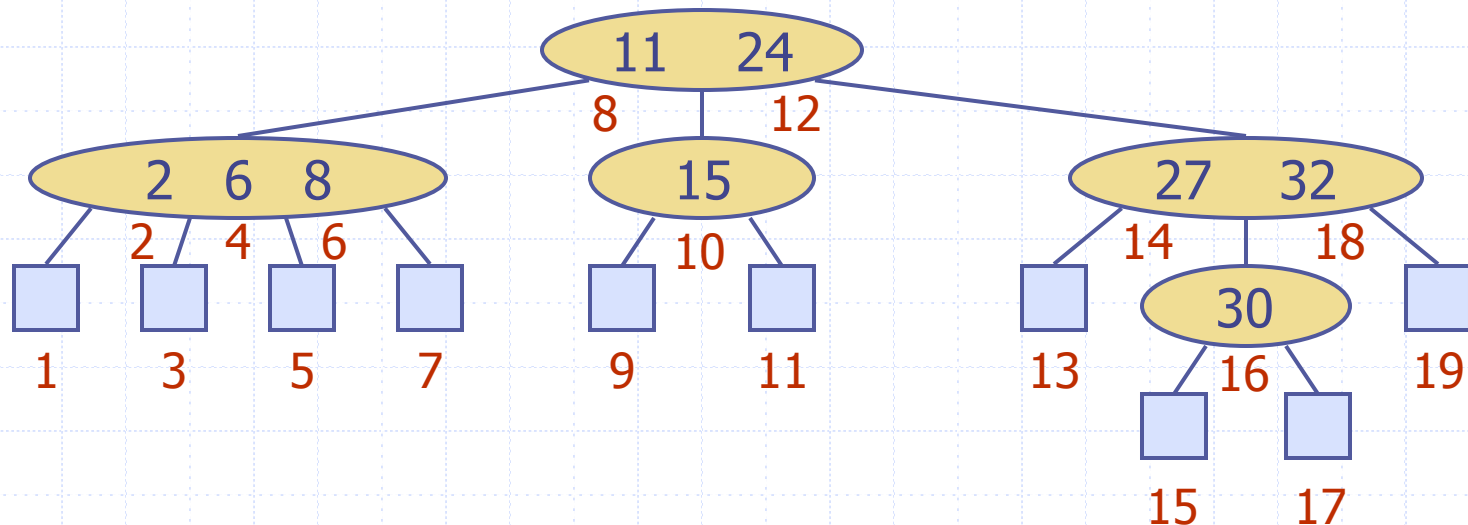
# Multi-Way Search Tree

- ◆ 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



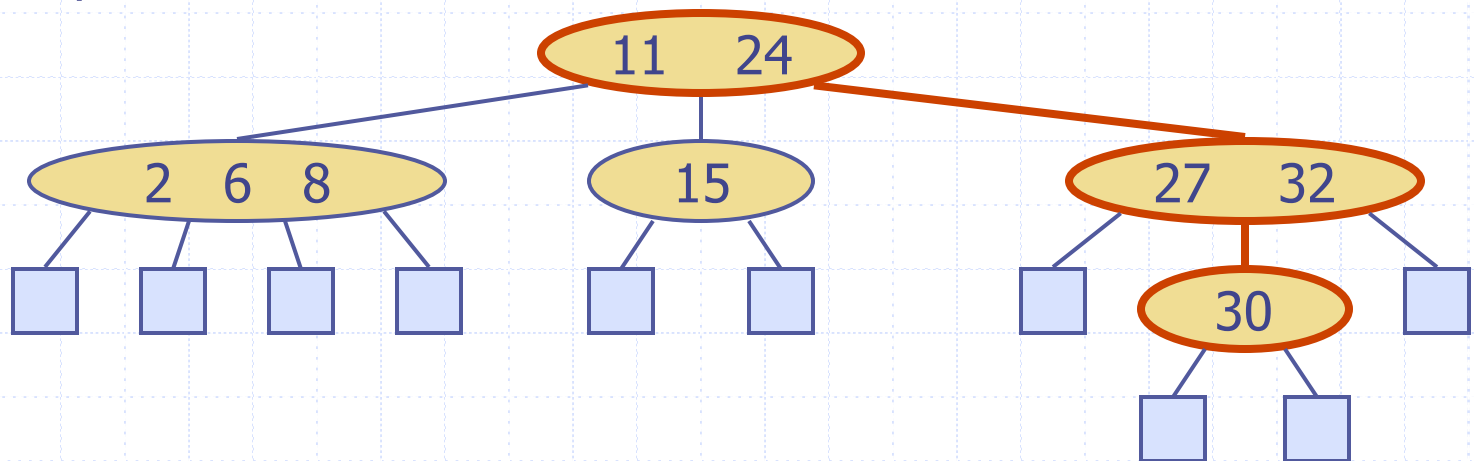
# Multi-Way Inorder Traversal

- ◆ 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



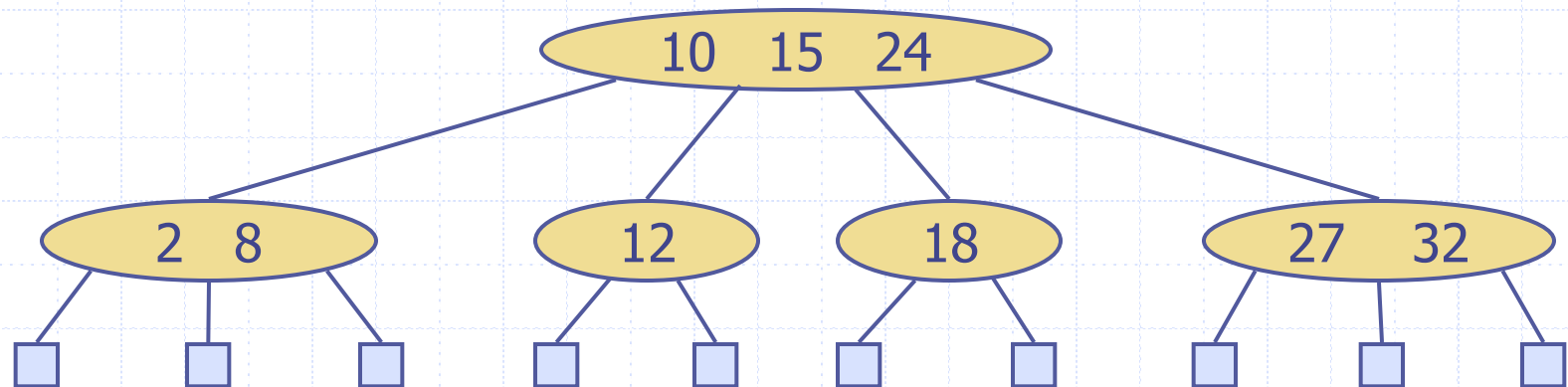
# Multi-Way Searching

- ◆ Similar to search in a binary search tree
- ◆ At 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
  - **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  $O(\log n)$

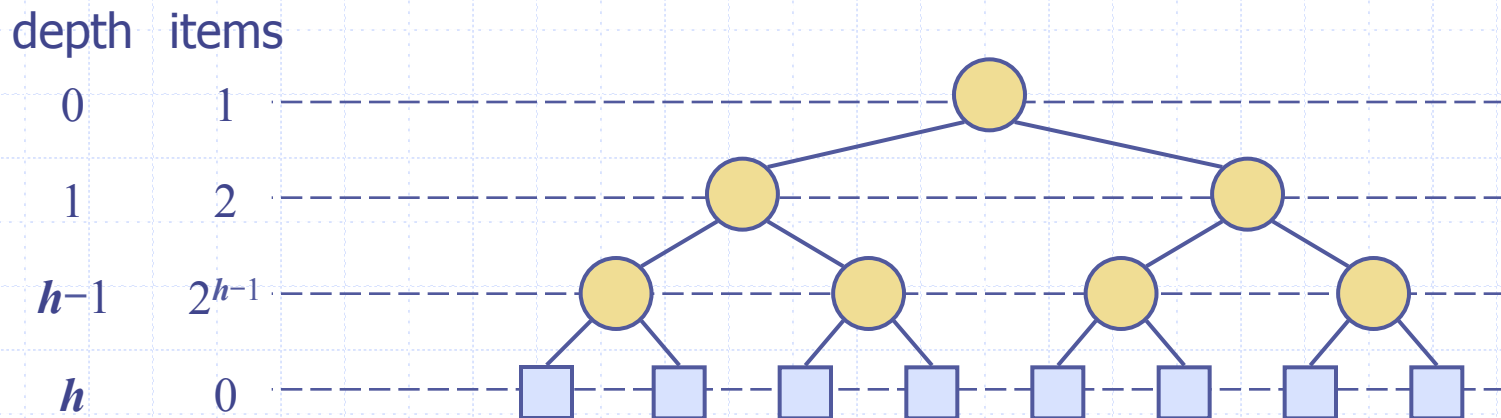
Proof:

- Let  $h$  be the height of a (2,4) tree with  $n$  items
- Since there are at least  $2^i$  items at depth  $i = 0, \dots, h-1$  and no items at depth  $h$ , we have

$$n \geq 1 + 2 + 4 + \dots + 2^{h-1} = 2^h - 1$$

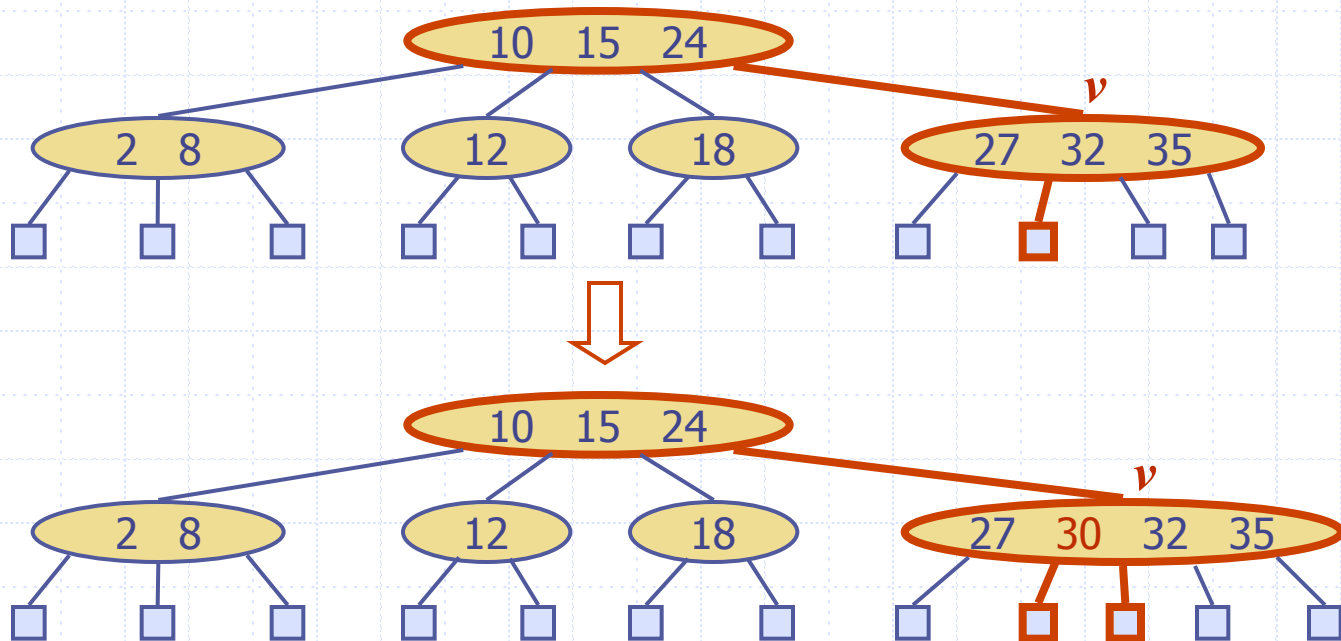
- Thus,  $h \leq \log(n + 1)$

◆ **Searching** in a (2,4) tree with  $n$  items takes  $O(\log n)$  time



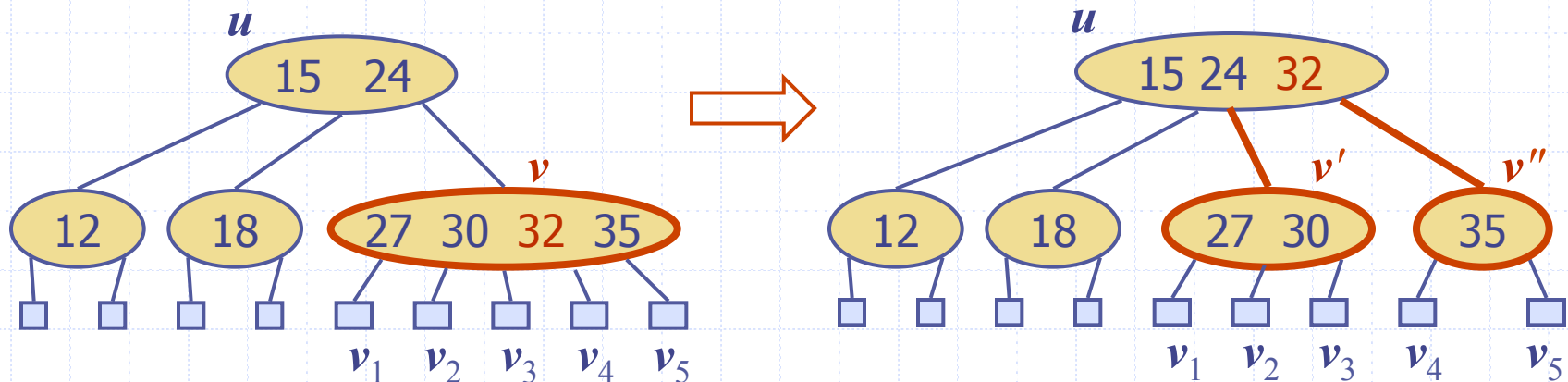
# Insertion

- ◆ 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  $v_1 \dots v_5$  be the children of  $v$  and  $k_1 \dots k_4$  be the keys of  $v$
  - node  $v$  is replaced 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

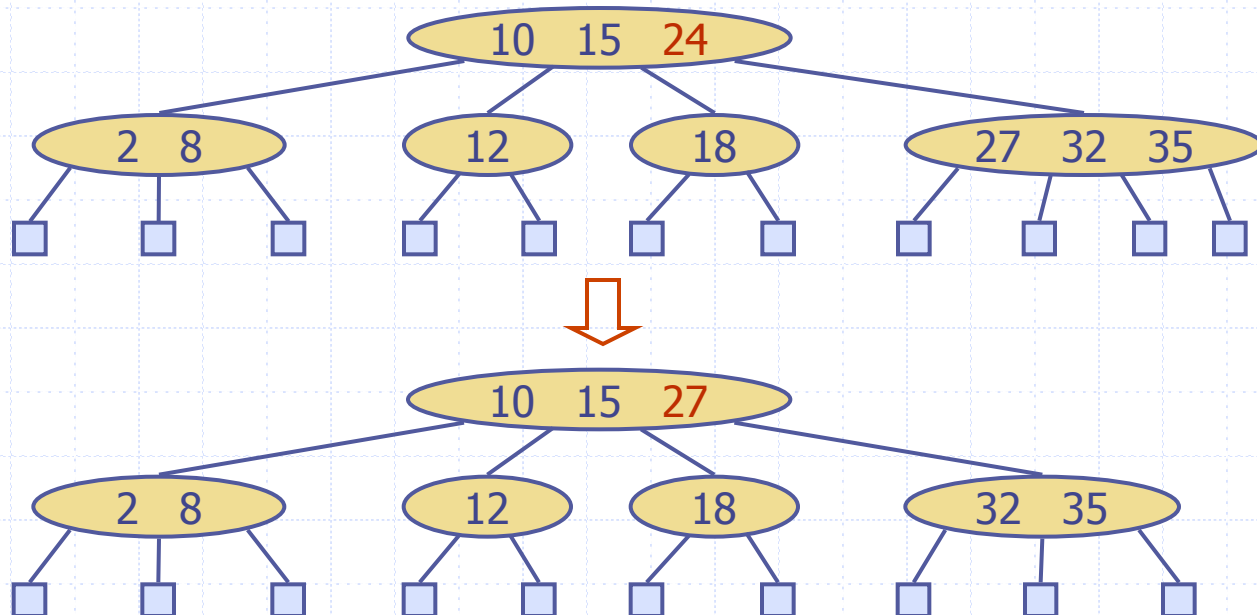
## Algorithm *put*( $k, o$ )

1. We search for key  $k$  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  $v$   
     $v \leftarrow \textit{split}(v)$

- ◆ 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

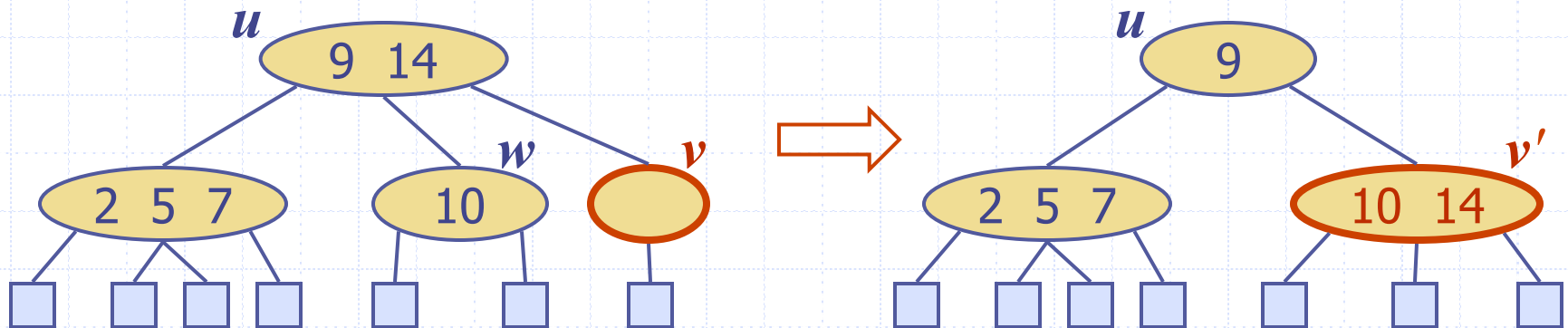
# Deletion

- ◆ 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)



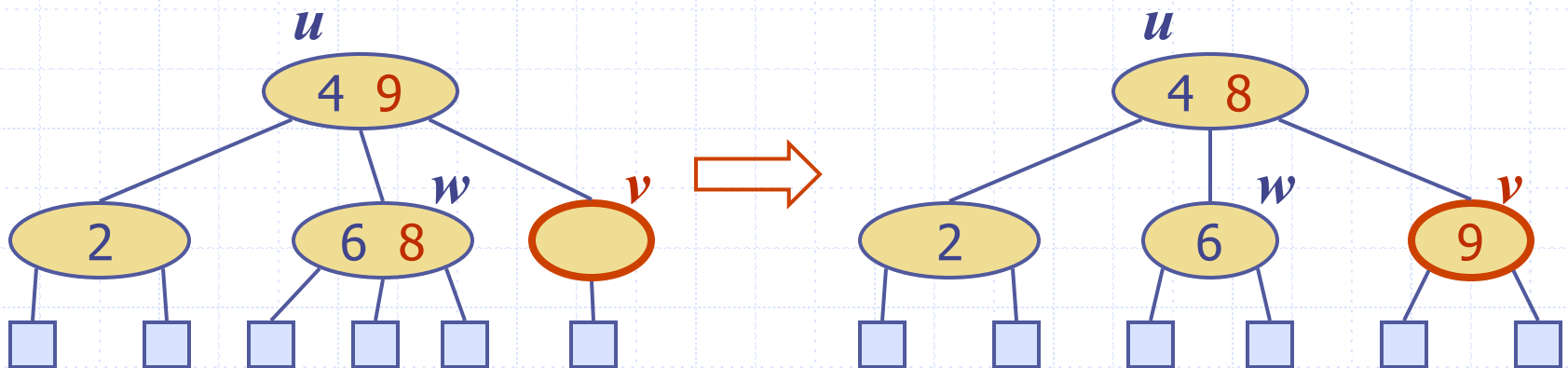
# Underflow and Fusion

- ◆ 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

	Get	Put	Delete	Notes
Hash Table	1 expected	1 expected	1 expected	<ul style="list-style-type: none"><li>no ordered map methods</li><li>simple to implement</li></ul>
Skip List	$\log n$ high prob.	$\log n$ high prob.	$\log n$ high prob.	<ul style="list-style-type: none"><li>randomized insertion</li><li>simple to implement</li></ul>
AVL and (2,4) Tree	$\log n$ worst-case	$\log n$ worst-case	$\log n$ worst-case	<ul style="list-style-type: none"><li>complex to implement</li></ul>