CS 240 – Data Structures and Data Management

Module 11: External Memory

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Based on lecture notes by many previous cs240 instructors

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Outline

- External Memory
  - Motivation
  - Stream based algorithms
  - External dictionaries
    - 2-4 Trees
    - red-black trees
    - *a*-*b* Trees
    - B-Trees

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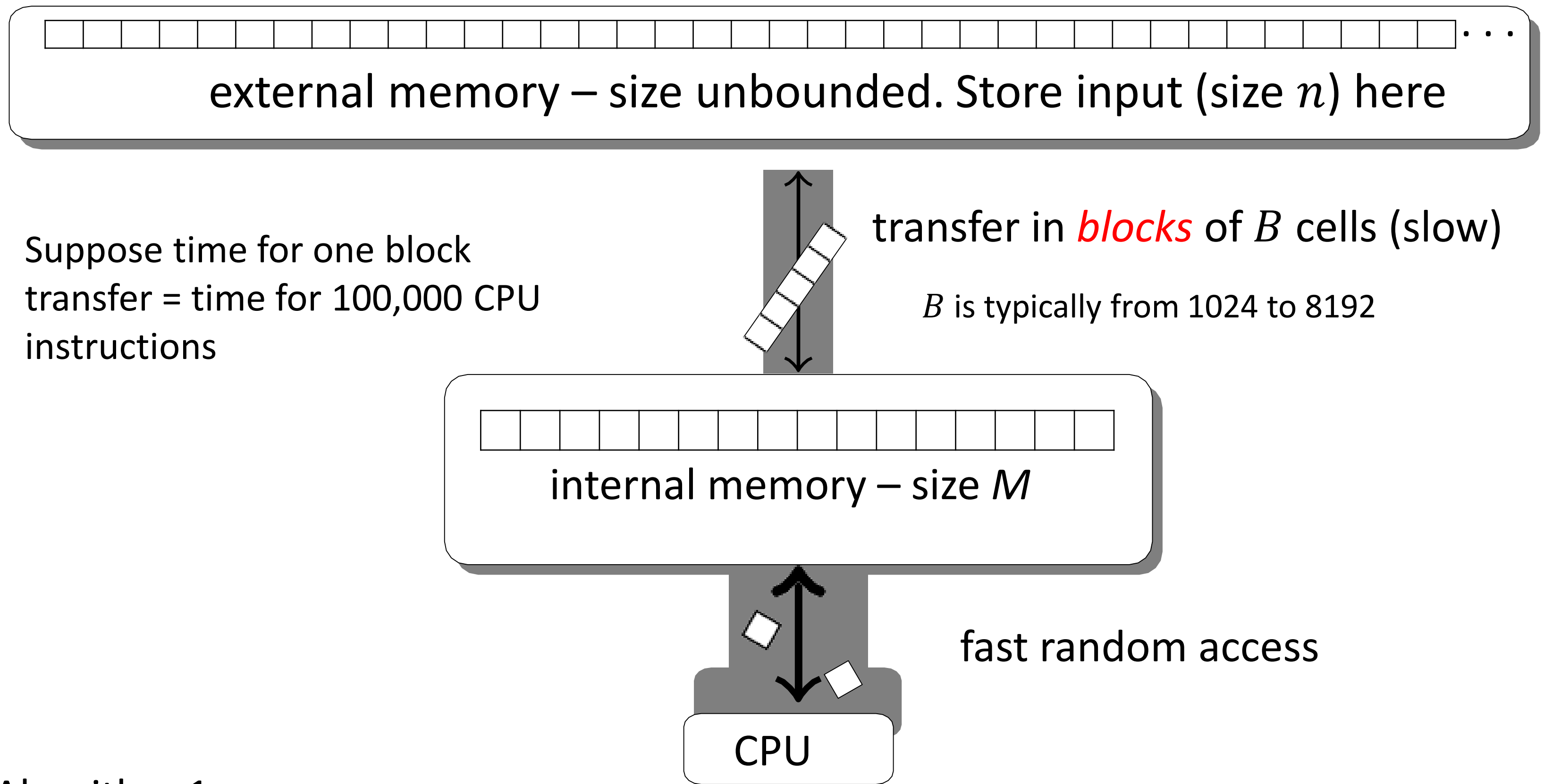
Different levels of memory

- RAM model: access to any memory location takes constant time
    - not realistic
- Current architectures
    - registers: super fast, very small
    - cache L1, L2: very fast, less small
    - main memory: fast, large
    - disk or cloud: slow, very large
- How to adapt algorithms to take memory hierarchy into consideration?
    - desirable to minimize transfer between slow/fast memory
- Define computer model that models hierarchy across which must transfer
    - focus on 2 levels of hierarchy: main (internal) memory and disk or cloud (external) memory
    - accessing a single location in external memory automatically loads a whole block (or "page")
        - one block access can take as much time as executing 100,000 CPU instructions
        - need to care about the number of block accesses

External-Memory Model (EMM)



Suppose time for one block transfer = time for 100,000 CPU instructions

- Algorithm 1
  ~~1,000 CPU instructions~~ + 1,000 block transfers = ~~1,000~~+1,000·100,000 = ~~10^3~~ + 10^8
- Algorithm 2
  ~~10,000 CPU instructions~~ + 10 block transfers = ~~10,000~~+10·100,000 = ~~10^4~~ + 10^6

dominating factors

- **New cost of computation:** number of blocks transferred (or 'probes', 'disk transfers', 'page loads') between internal and external memory
- We will revisit ADTs/problems with the objective of minimizing block transfers

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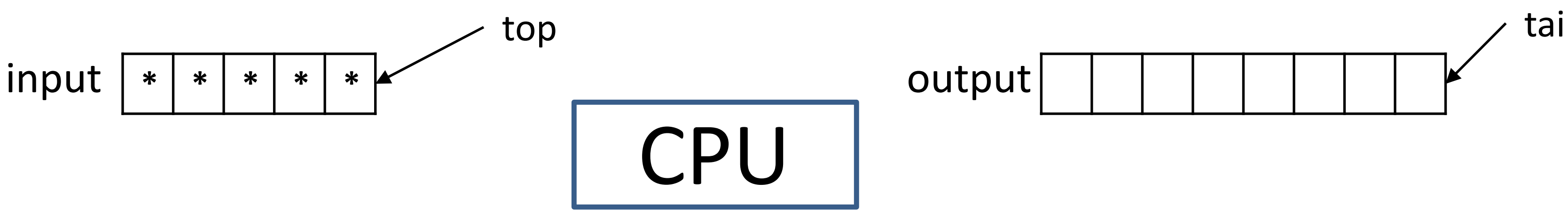
Stream Based Algorithms in Internal Memory

- Studied algorithms that handle input/output with streams
  - access only top item in input stream, append only to tail of output stream



- Repeat
  1. take item off top of the input
  2. process item
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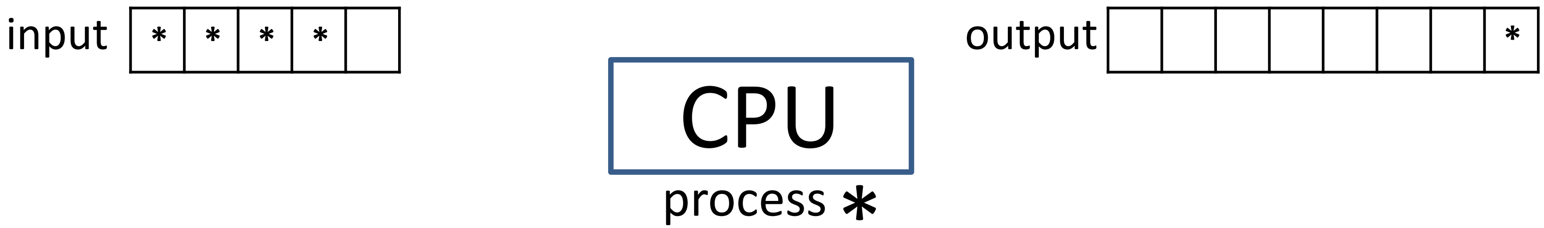

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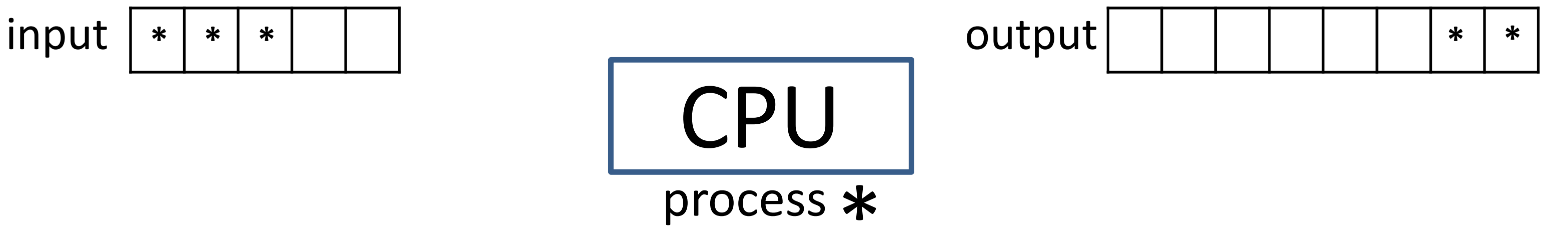

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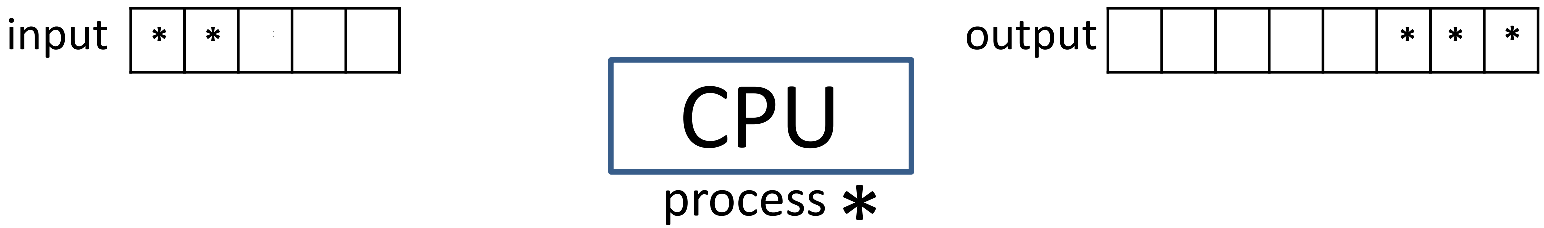

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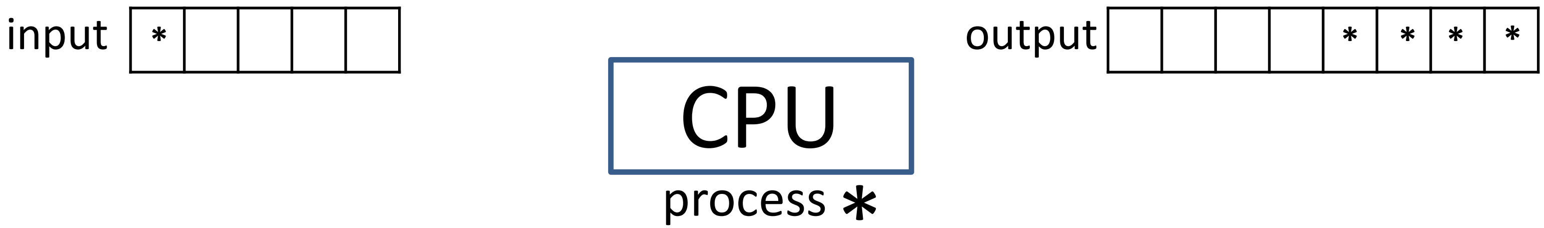

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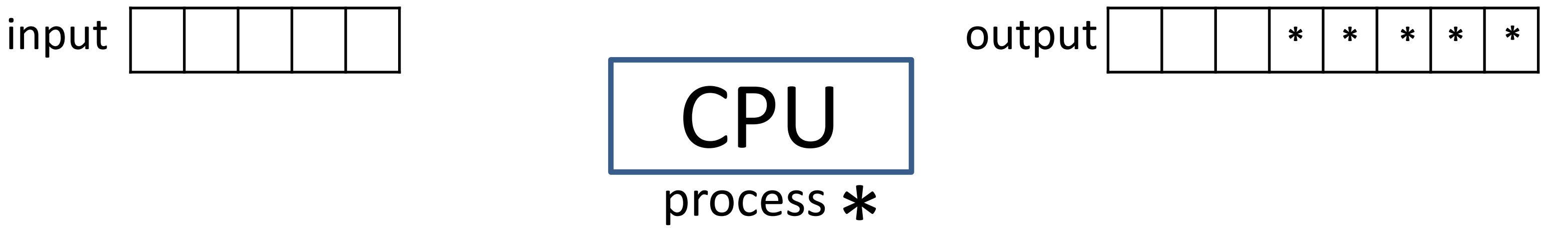

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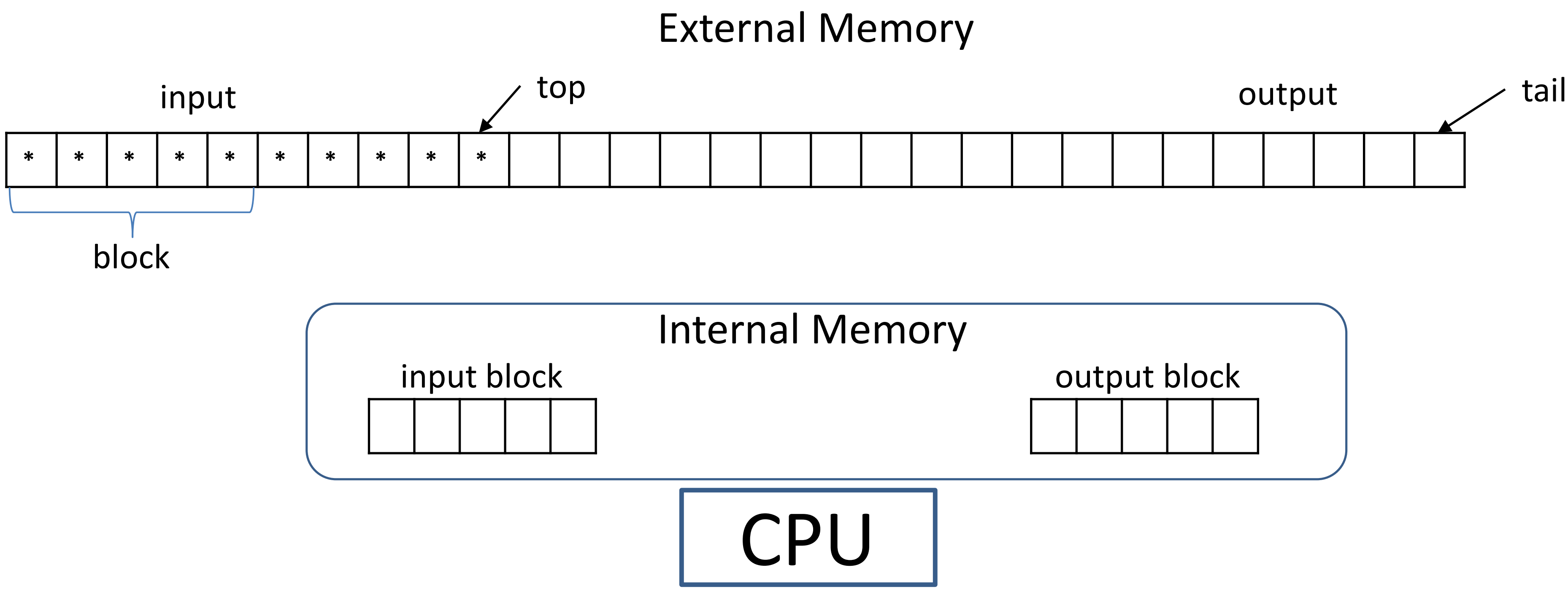
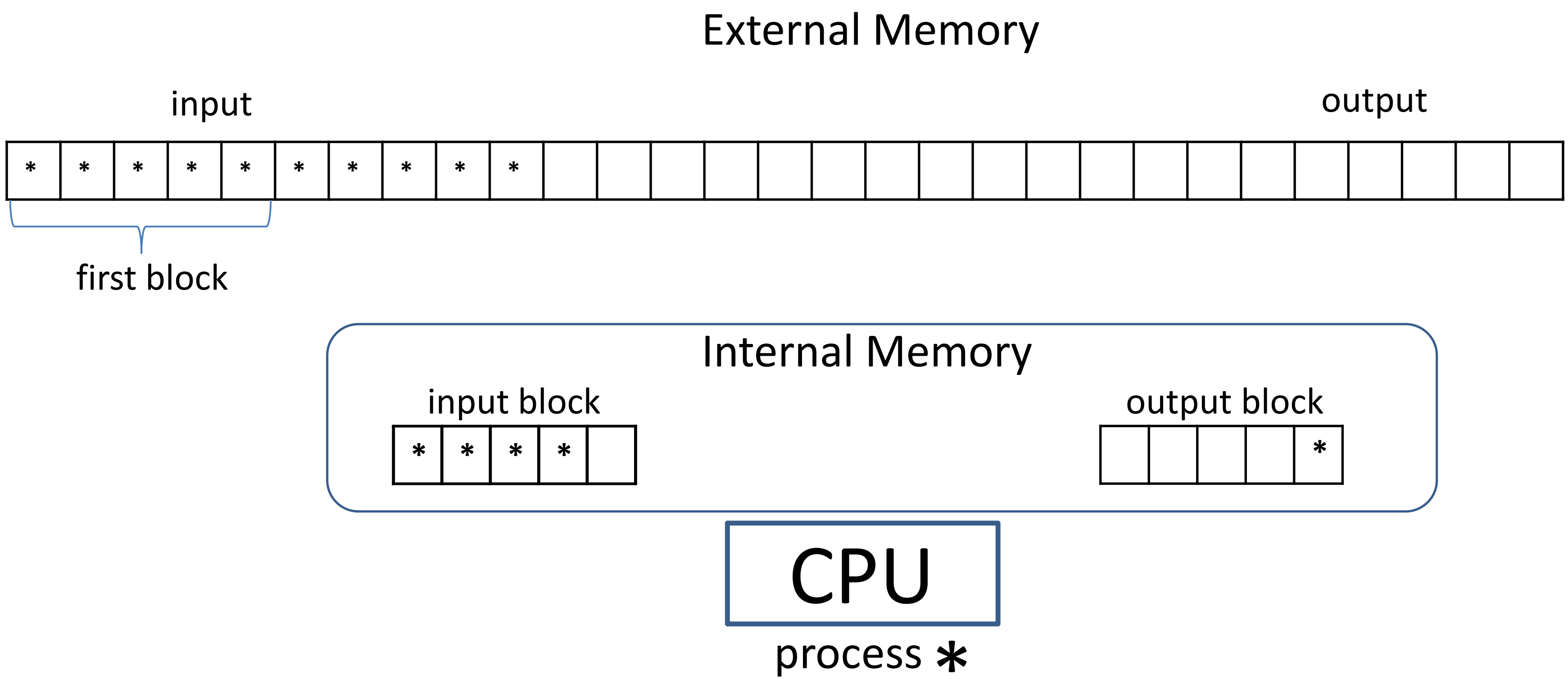
Stream Based Algorithms in External Memory



- Data in external memory has to be placed in internal memory before it can be processed
- Idea: perform the same algorithm as before, but in “block-wise” manner
  - have one block for input, one block for output in internal memory
  - transfer a block (size B) to internal memory, process it as before, store result in output block
  - when output stream is of size B (full block), transfer it to external memory
  - when current block is in internal memory is fully processed, transfer next unprocessed block from external memory

Stream Based Algorithms in External Memory



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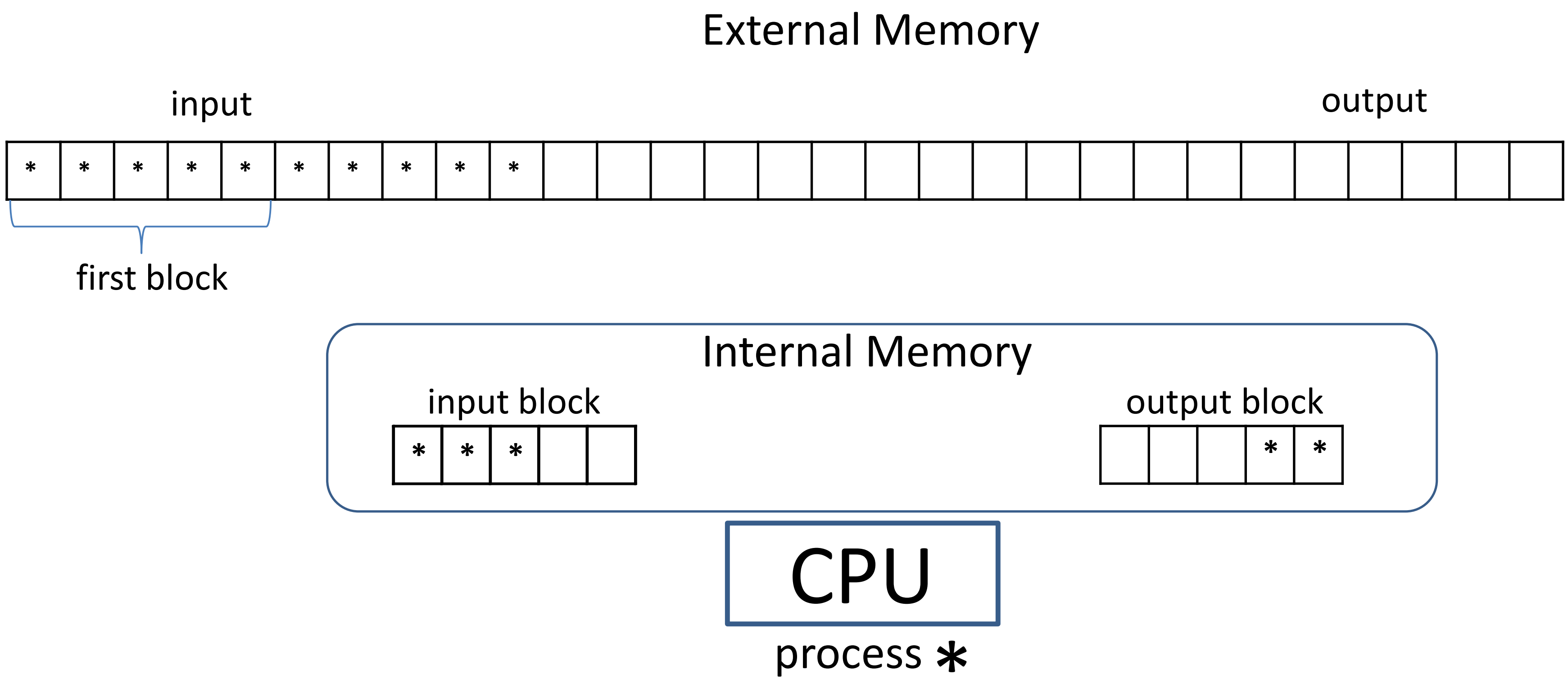

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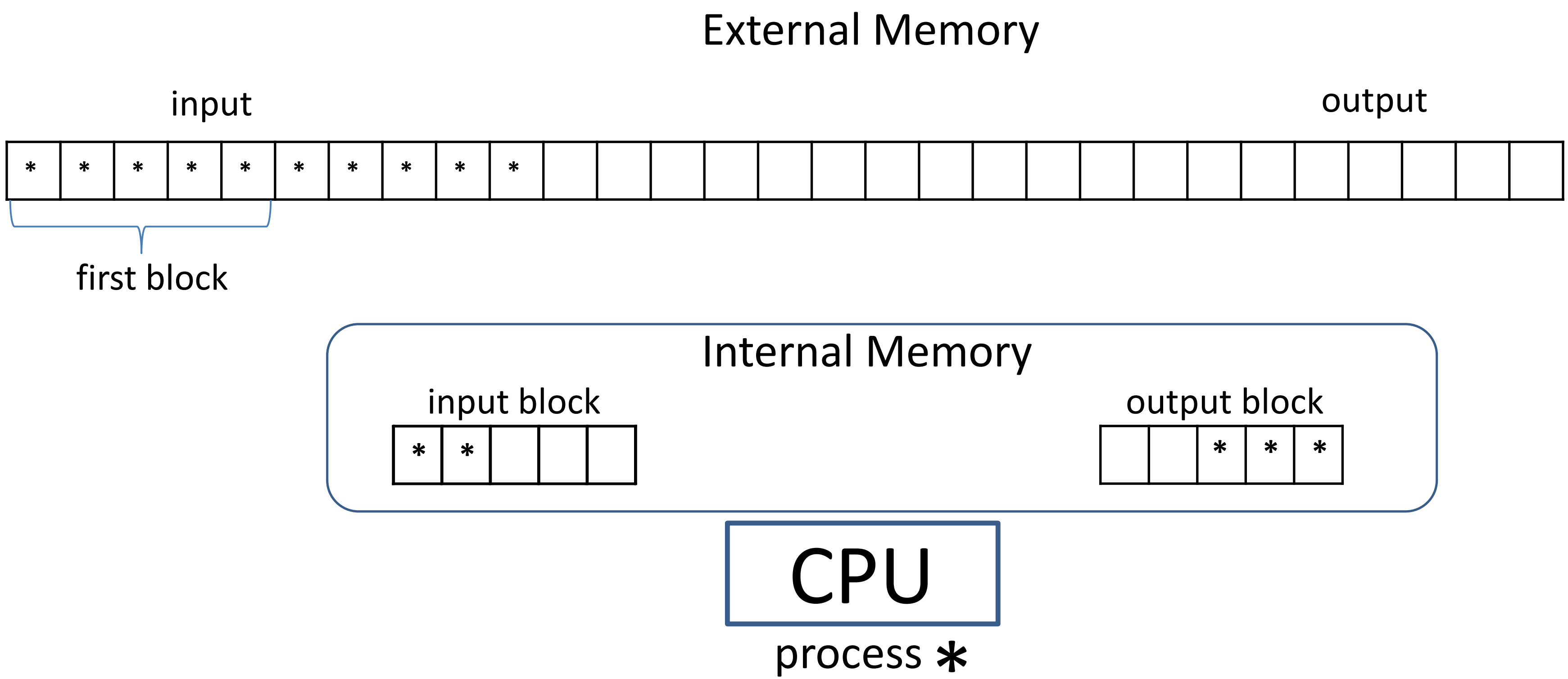

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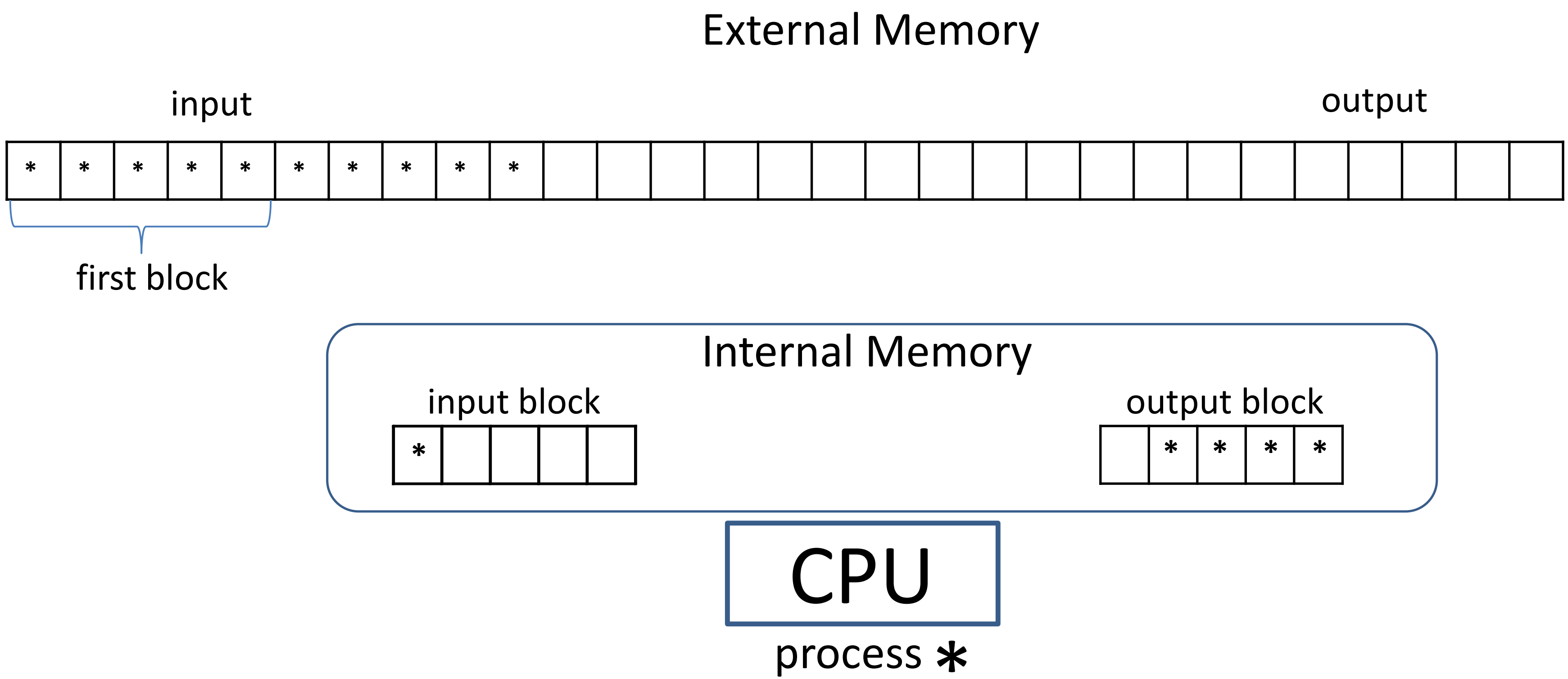

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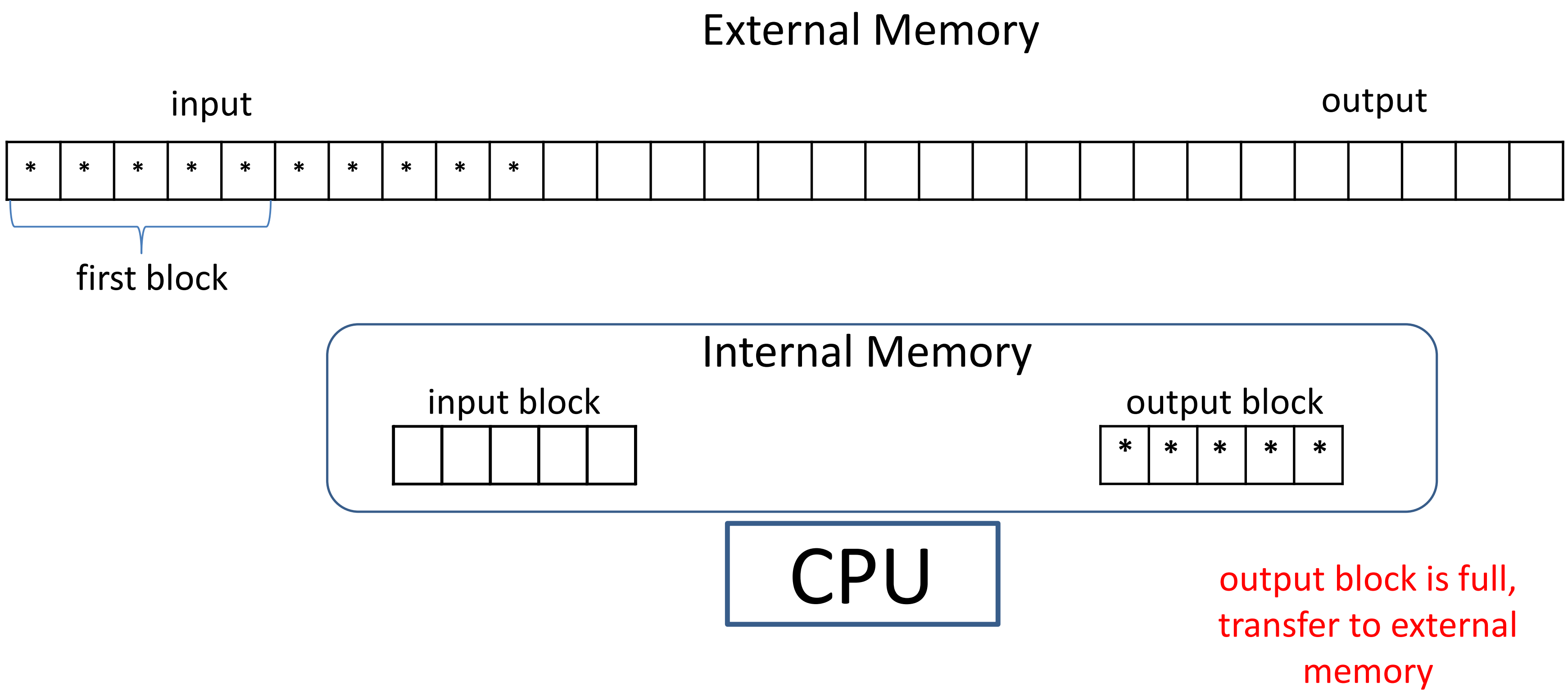

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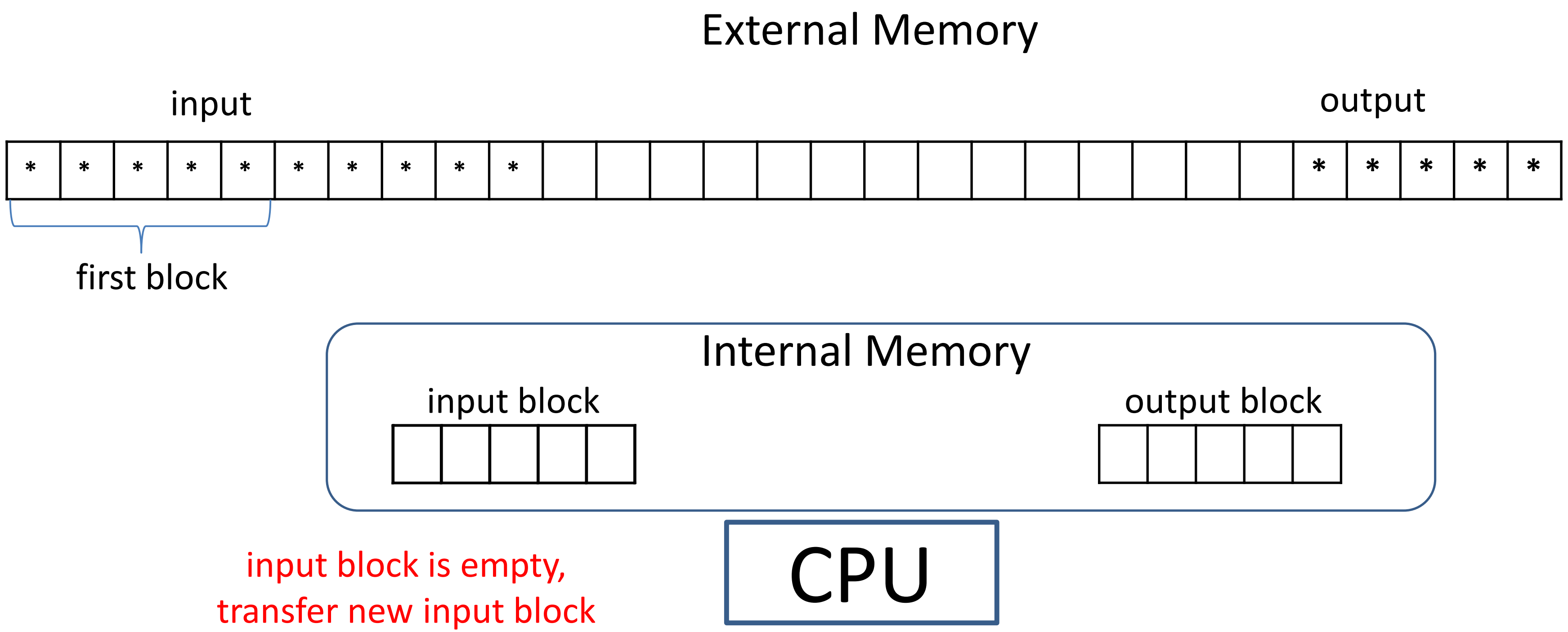
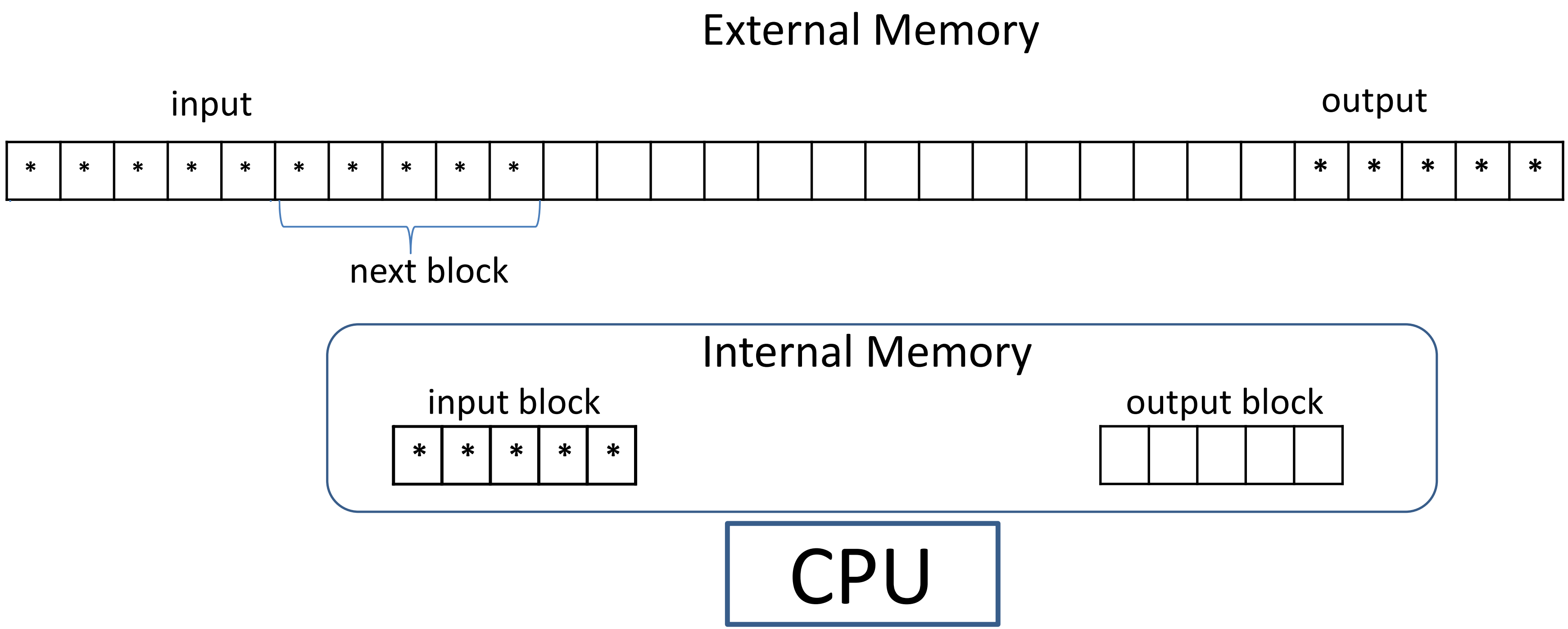
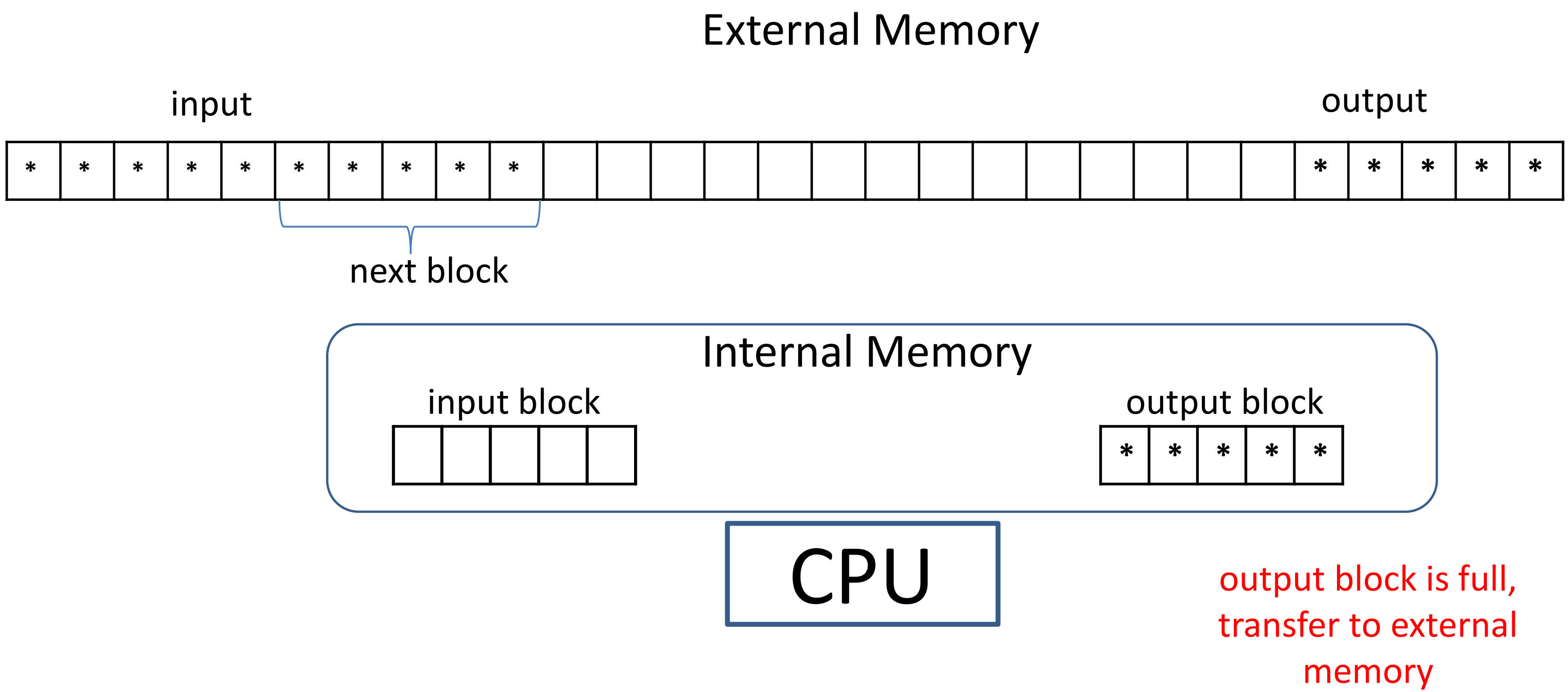


input block is empty,
transfer new input block
from external memory

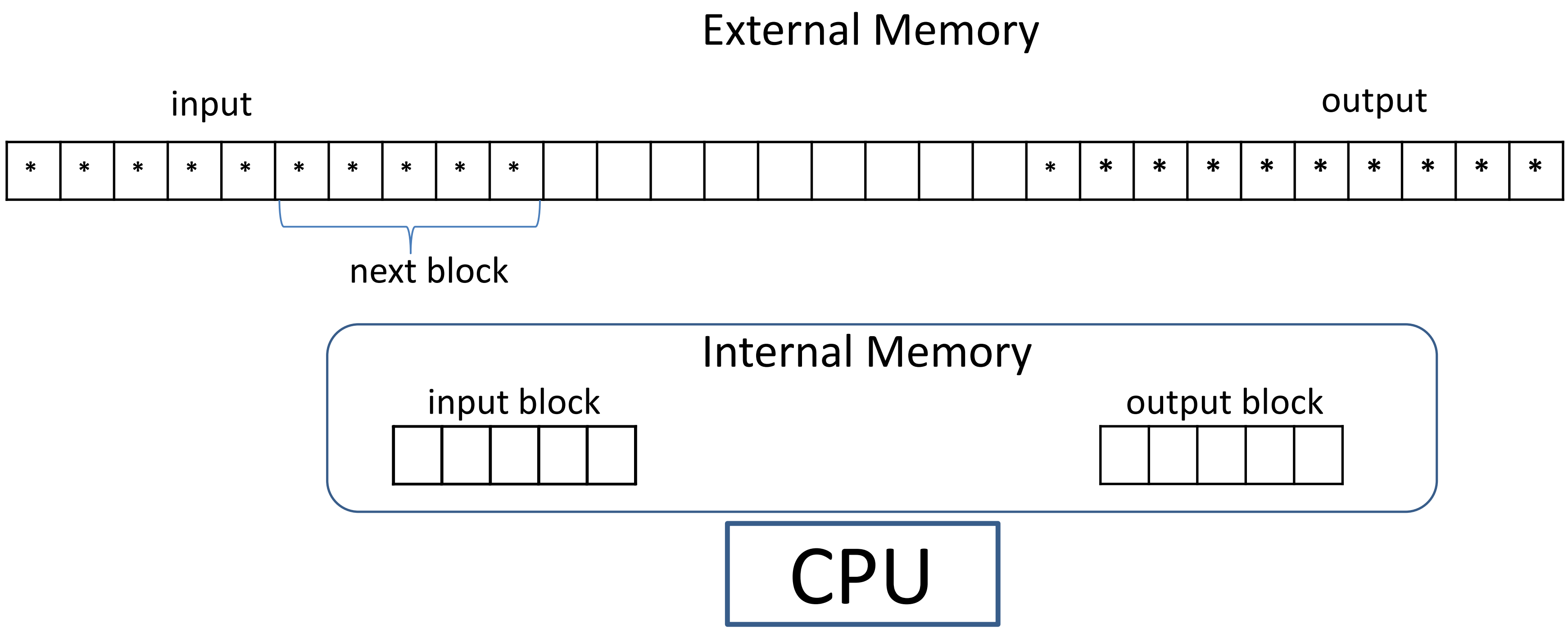
Stream Based Algorithms in External Memory



Stream Based Algorithms in External Memory



Stream Based Algorithms in External Memory



- Running time (recall that we only count the block transfers now)
  - input stream: $\frac{n}{B}$ block transfers to read input of size n
  - output stream: $\frac{s}{B}$ block transfers to write output of size s
- Running time is *automatically* as efficient as possible for external memory
  - any algorithm needs at least $\frac{n}{B}$ block transfers to read input of size n and $\frac{s}{B}$ block transfers to write output of size s

Stream Based Algorithms in External Memory

- Methods below use stream input/output model, therefore need $\Theta\left(\frac{n}{B}\right)$ block transfers, assuming output size is $O(n)$
  - Pattern matching: Karp-Rabin, Knuth-Morris-Pratt, Boyer-Moore
    - assuming pattern P fits into internal memory
  - Text compression: Huffman, run-length encoding, Lempel-Ziv-Welch
  - Sorting: *merge-sort* can be implemented with $O\left(\frac{n}{B}\log n\right)$ block transfers
  - Bzip2 cannot be streamed as we described
    - can compress in ‘blocks’
      - not as good as the whole text compression, but better than nothing

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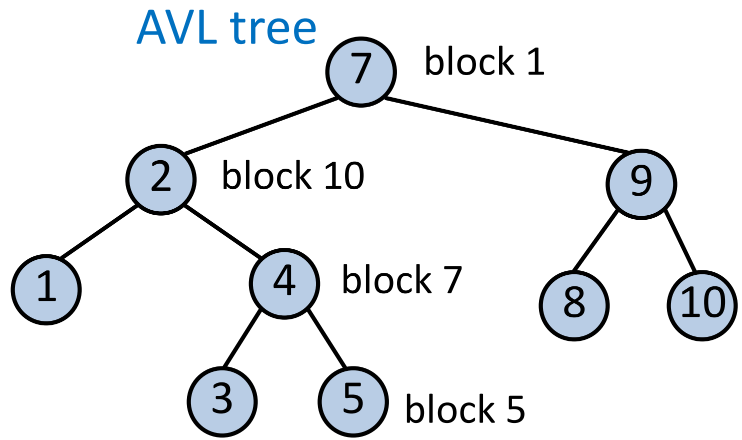
Dictionaries in External Memory: Motivation



- AVL tree based dictionary implementations have poor *memory locality*
  - 'nearby' tree nodes are unlikely to be in the same block

- In an AVL tree $\Theta(\log n)$ blocks are loaded in the worst case
- Idea: allow trees that store multiple items per node
- Many items per node $\Longrightarrow$ smaller height $\Longrightarrow$ fewer block transfers
  - suppose store $n = 2^{50}$ items total, and $B = 2^{15}$ items in each node
  - tree height is $\log_B n \;= \dfrac{\log_2 n}{\log_2 B} = \dfrac{50}{15}$
  - 15 times less block transfers
- First consider a special case: *2-4 trees*
  - 2-4 trees also used for dictionaries in internal memory
  - may be even faster than AVL-trees

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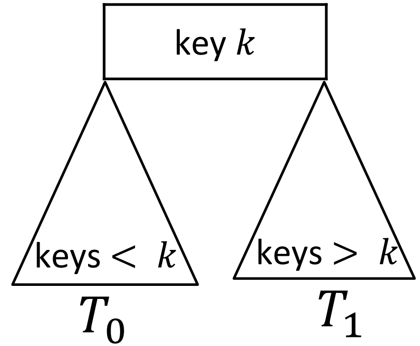
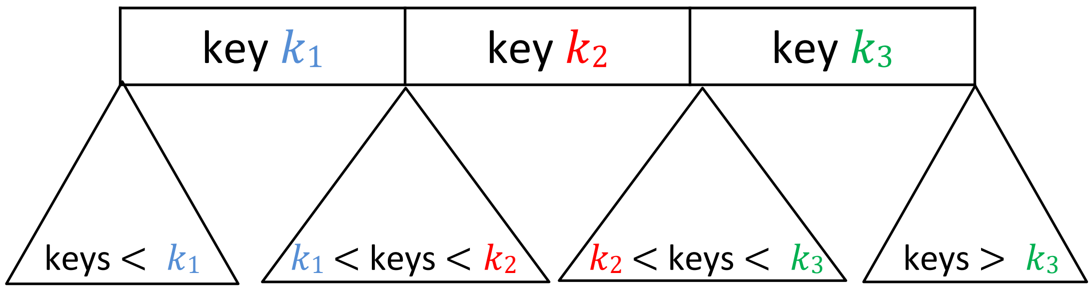
2-4 Trees Motivation



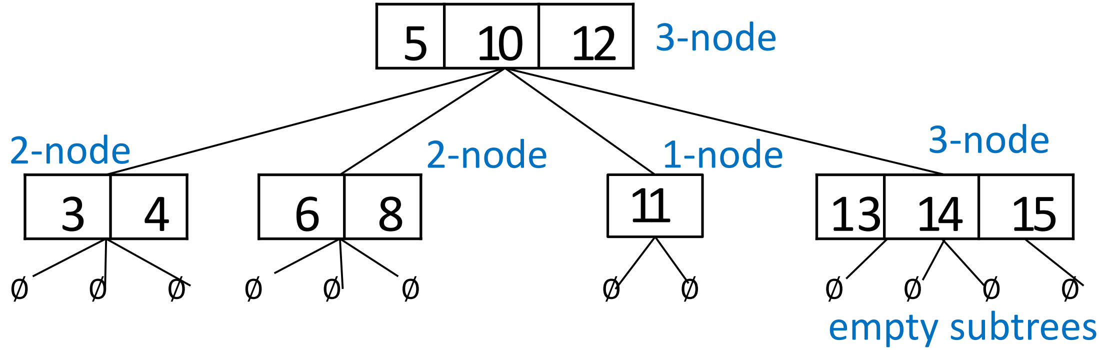
- Binary Search Tree supports efficient search with special key ordering

- Need nodes that store more than one key
  - how to support efficient search?

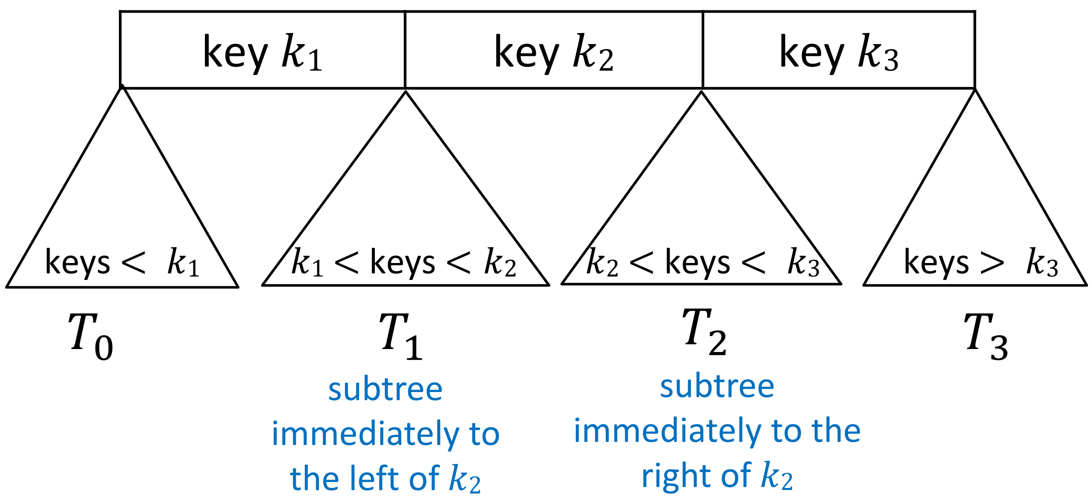


- Need additional properties to ensure tree is balanced and therefore *insert*, *delete* are efficient

2-4 Trees



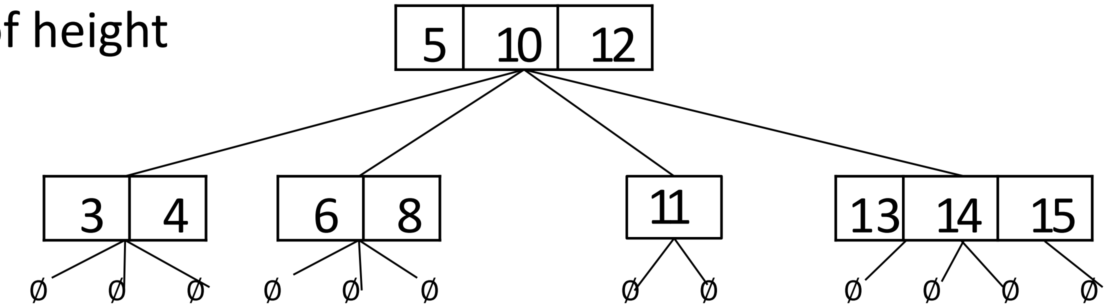
- **Structural properties**
  - Every node is either
    - 1-node: *one KVP* and *two subtrees* (possibly empty), or
    - 2-node: *two KVPs* and *three subtrees* (possibly empty), or
    - 3-node: *three KVPs* and *four subtrees* (possibly empty)
    - allowing 3 types of nodes simplifies insertion/deletion
  - All empty subtrees are at the same level
    - necessary for ensuring height is logarithmic in the number of KVP stored
- **Order property:** keys at any node are between the keys in the subtrees



key-subtree list of the node
$< T_0, k_1, T_1, k_2, T_2, k_3, T_3, k_1 >$

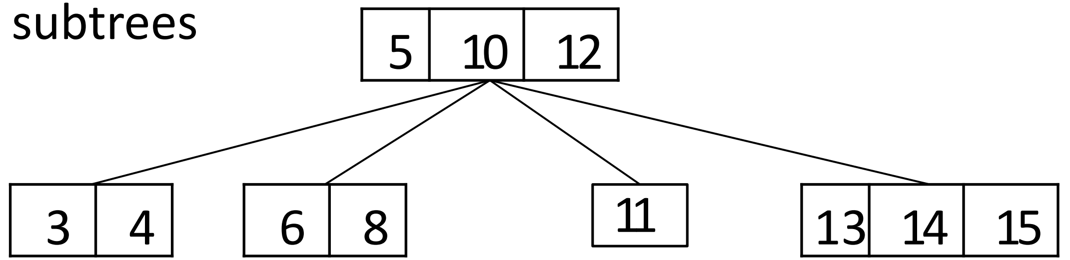
2-4 Tree Example

- Empty subtrees are not part of height computation



tree of height 1

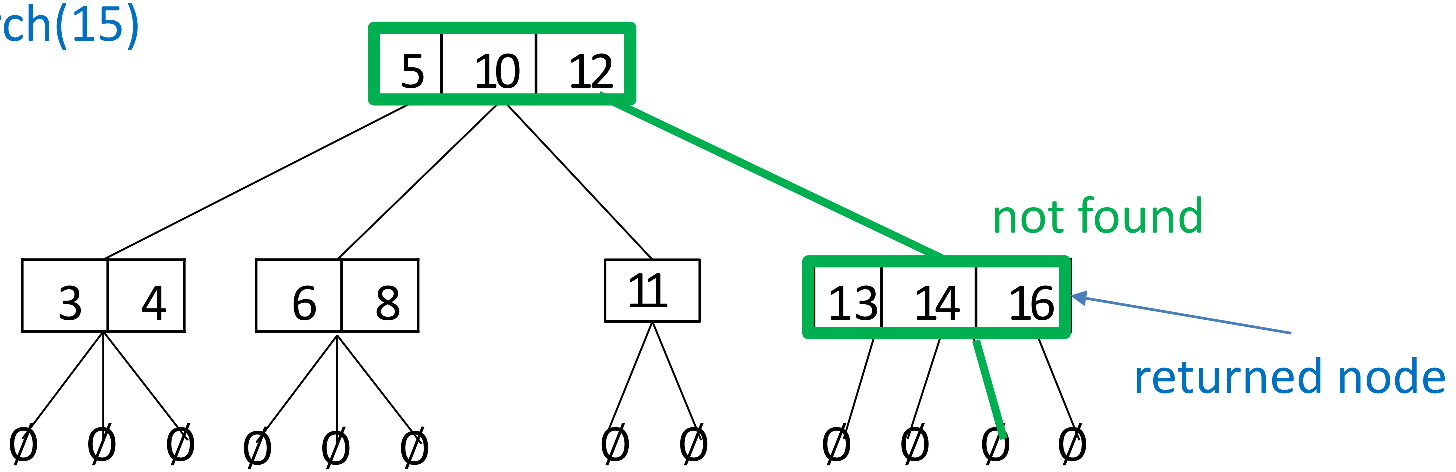
- Often do not even show empty subtrees



- Will prove height is $O(\log n)$ later, when we talk about (a,b)-trees
  - 2-4 tree is a special type of (a,b)-tree

2-4 Tree: Search Example

- **Search**
  - similar to search in BST
  - search(k) compares key k to k_1, k_2, k_3, and either finds k among k_1, k_2, k_3 or figures out which subtree to recurse into
  - if key is not in tree, search returns parent of empty tree where search stops
    - key can be inserted at that node
  - search(15)



2-4 Tree operations

24Tree::search$(k, v \leftarrow$root$, p \leftarrow$empty subtree)

k: key to search, v: node where we search; p: parent of v

if v represents empty subtree

return "not found, would be in p"

let $< T_0, k_1, \ldots, k_d, T_d >$ be key-subtrees list at v

if $k \geq k_1$

$i \leftarrow$ maximal index such that $k_i \leq k$

if $k_i = k$

return "at ith key in v"

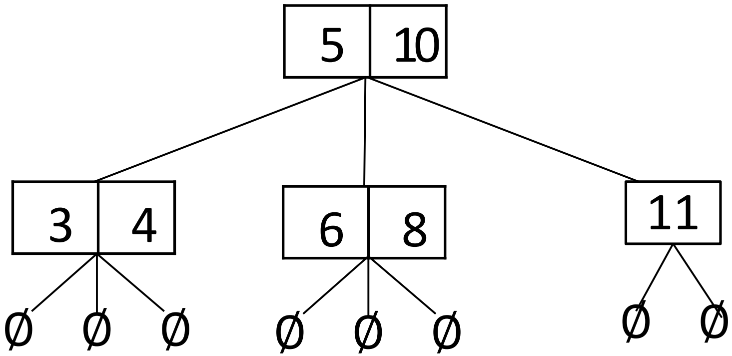
else *24Tree::search*(k, T_i, v)

else *24Tree::search*(k, T_0, v)

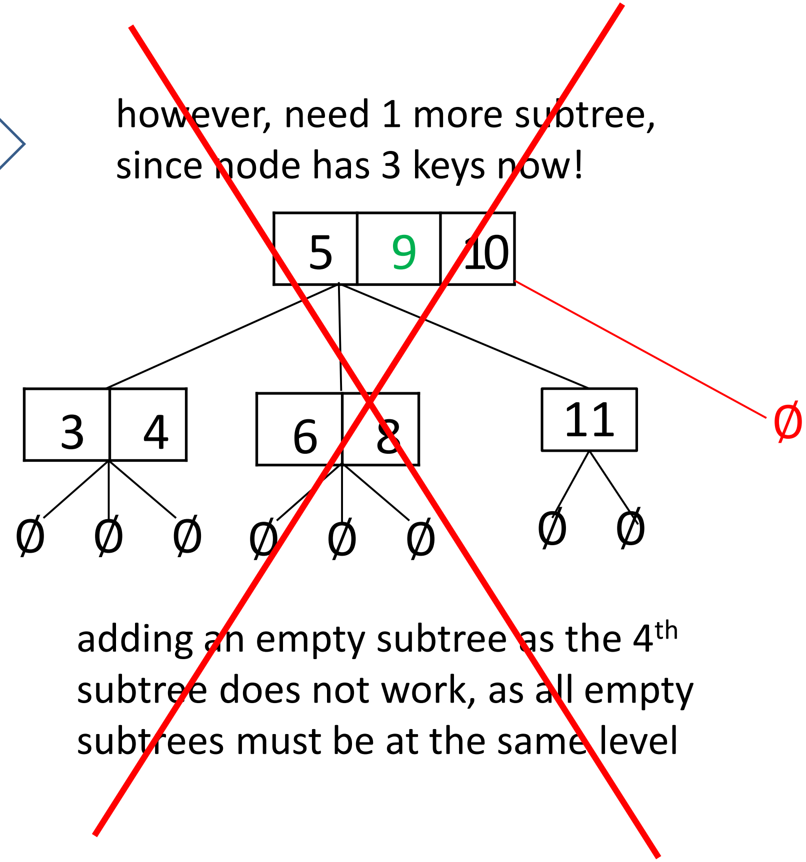
Example: 2-4 tree Insert

- **Example**: *24TreeInsert*(9)

node can hold one more item,
so it's tempting to insert 9 in it



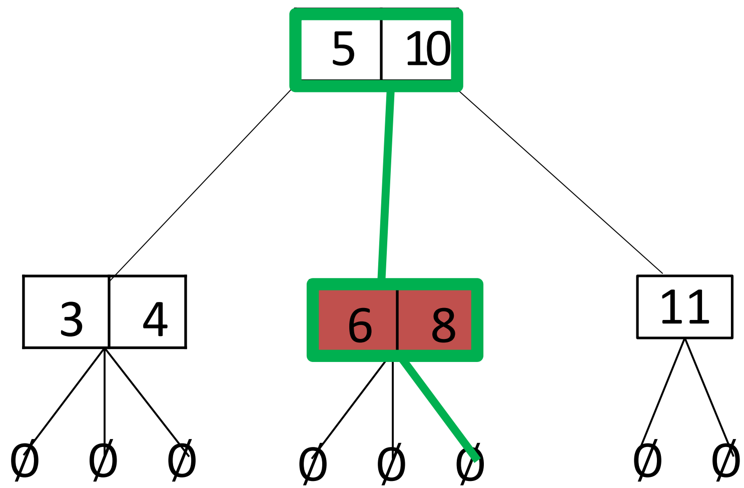
however, need 1 more subtree,
since node has 3 keys now!



adding an empty subtree as the 4th subtree does not work, as all empty subtrees must be at the same level

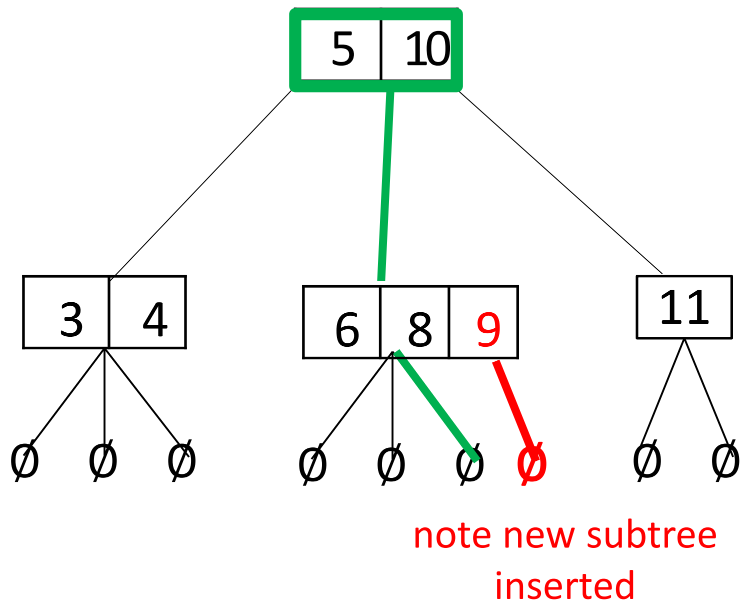
Example: 2-4 tree Insert

- **Example**: *24TreeInsert*(9)
  - first step: 24Tree::search(9)



Example: 2-4 tree Insert

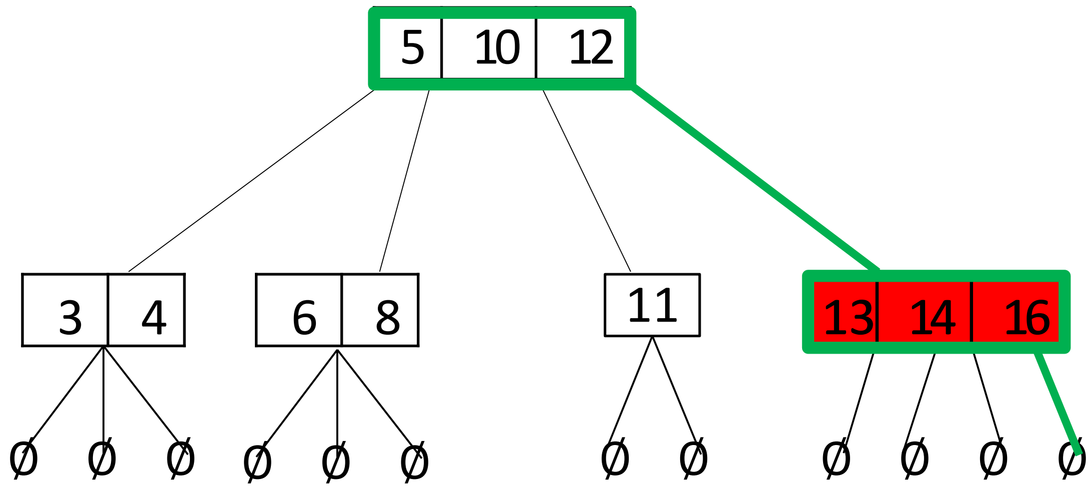
- **Example**: *24TreeInsert*(9)
  - first step: 24Tree::search(9)
  - second step: insert at the leaf node returned by search



- adding an empty subtree at the last level causes no problems
- order properties are preserved
- node stays valid, it now has 3 KVPs, which is allowed

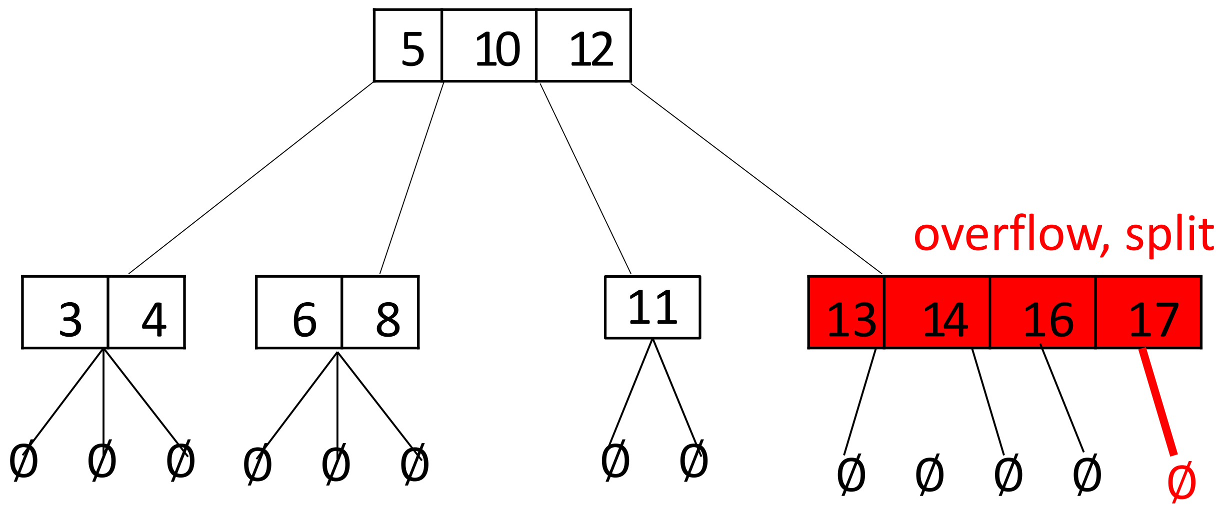
Example: 2-4 tree Insert

- **Example**: *24TreeInsert*(17)
    - first step is 24Tree::search(17)
    - insert at the leaf node returned by search



Example: 2-4 tree Insert

- **Example**: *24TreeInsert*(17)
  - now leaf has 4 KVPs, not allowed, have to fix this



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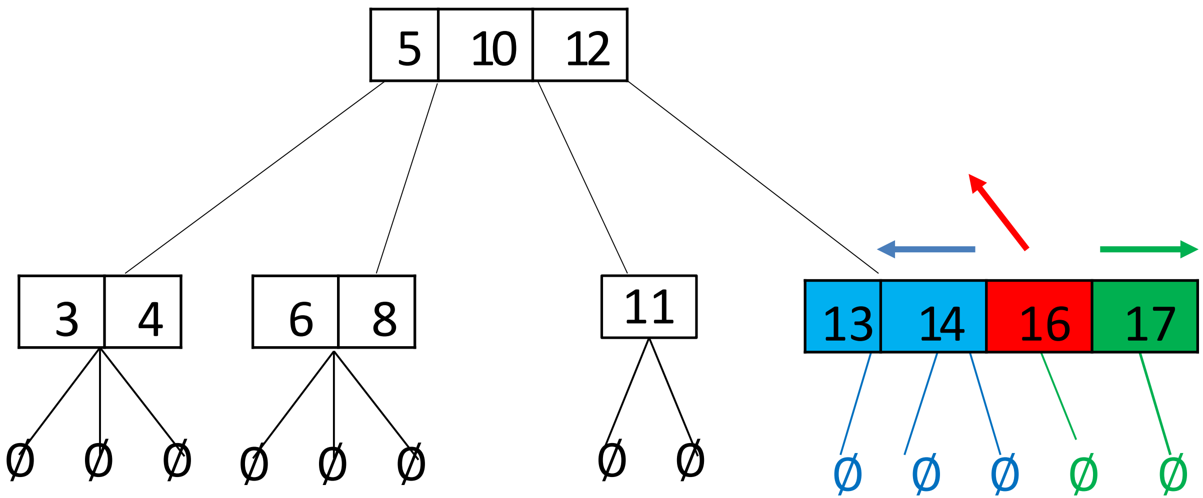
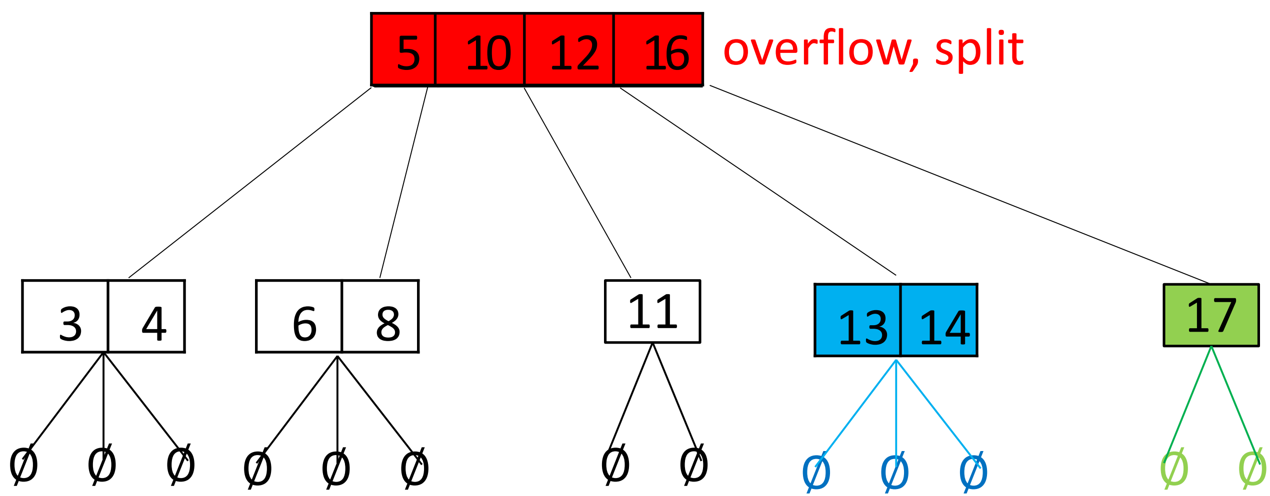


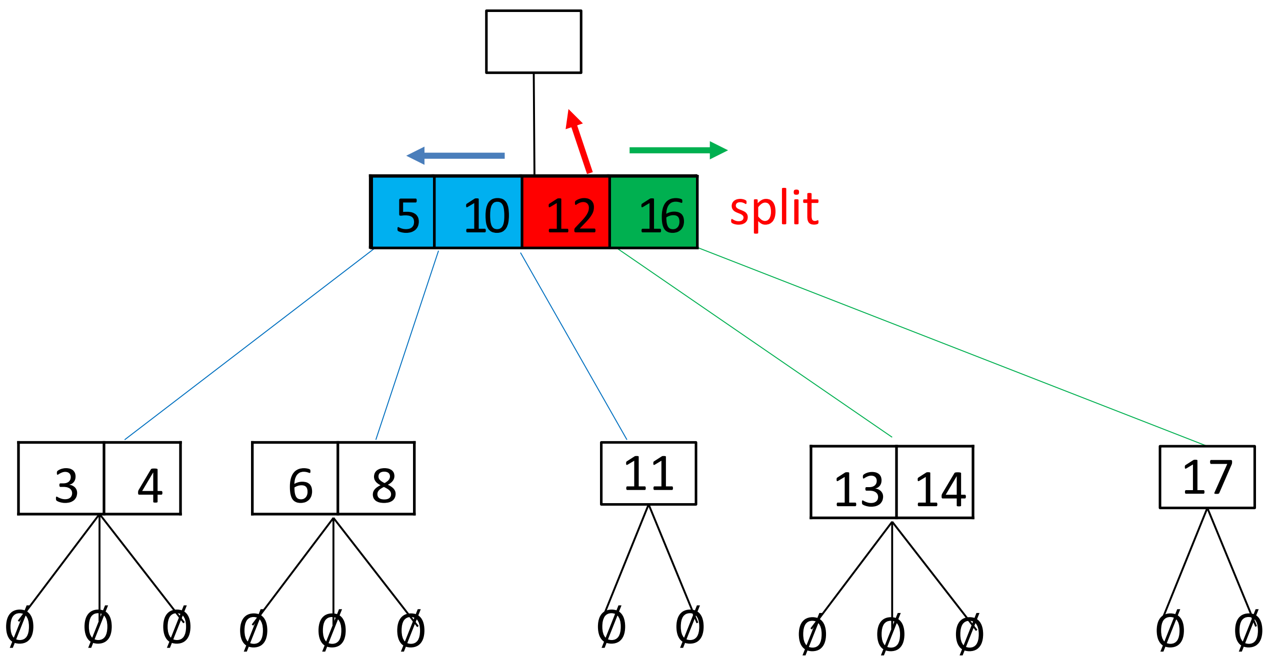
Example: 2-4 tree Insert

- **Example**: *24TreeInsert*(17)
  - splitting is possible because we allow variable node size
    - split 3-node into 1-node and 2-node
  - order property is preserved after a split
  - overflow can propagate to the parent of split node



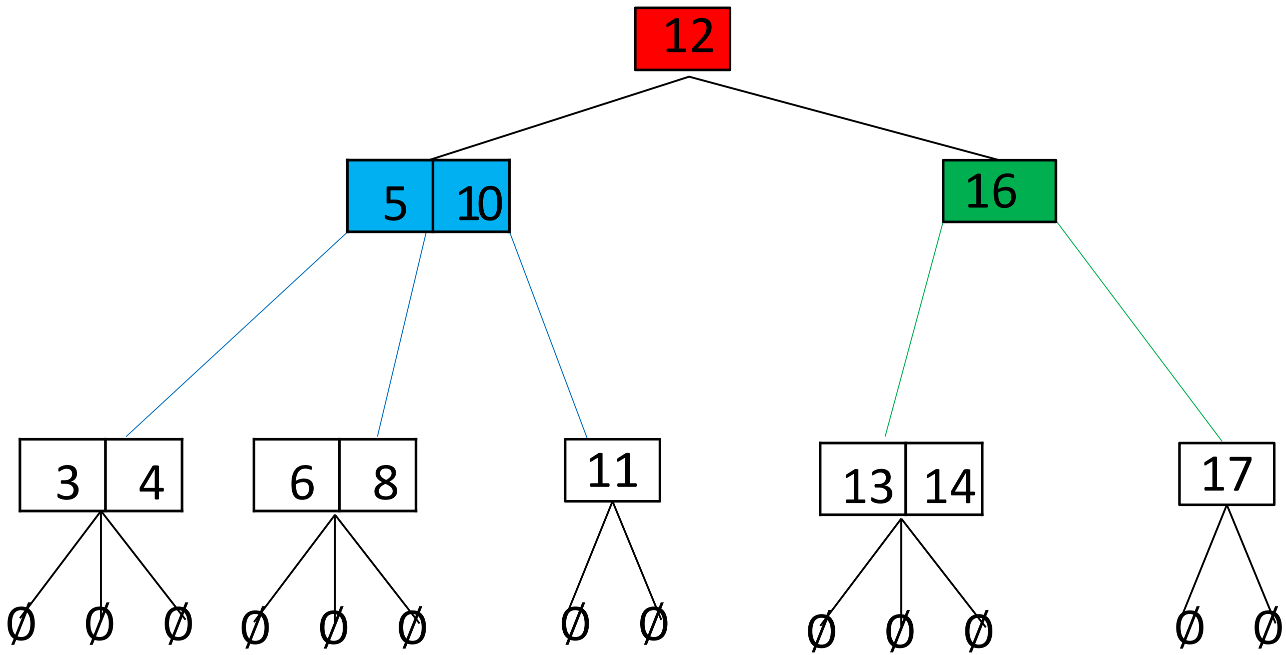
Example: 2-4 tree Insert

- **Example**: *24TreeInsert*(17)
  - when splitting the root node, need to create new root



Example: 2-4 tree Insert

- **Example**: *24TreeInsert*(17)



2-4 Tree Insert Pseudocode

24Tree::insert(k)

  $v \leftarrow$ *24Tree::search*(k) //leaf where *k* should be

  add k and an empty subtree in key-subtree-list of v

  while v has 4 keys (overflow → node split)

    let $< T_0, k_1, \ldots, k_4, T_4 >$ be key-subtrees list at v

    if v has no parent

      create an empty parent of v

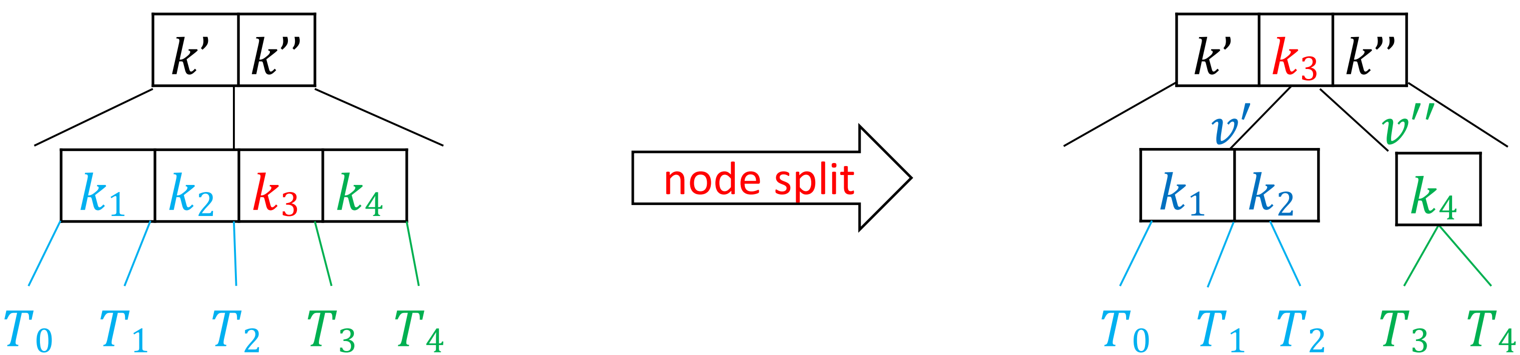
    $p \leftarrow$ parent of v

    $v' \leftarrow$ new node with keys k_1, k_2 and subtrees T_0, T_1, T_2

    $v'' \leftarrow$ new node with key k_4 and subtrees T_3, T_4

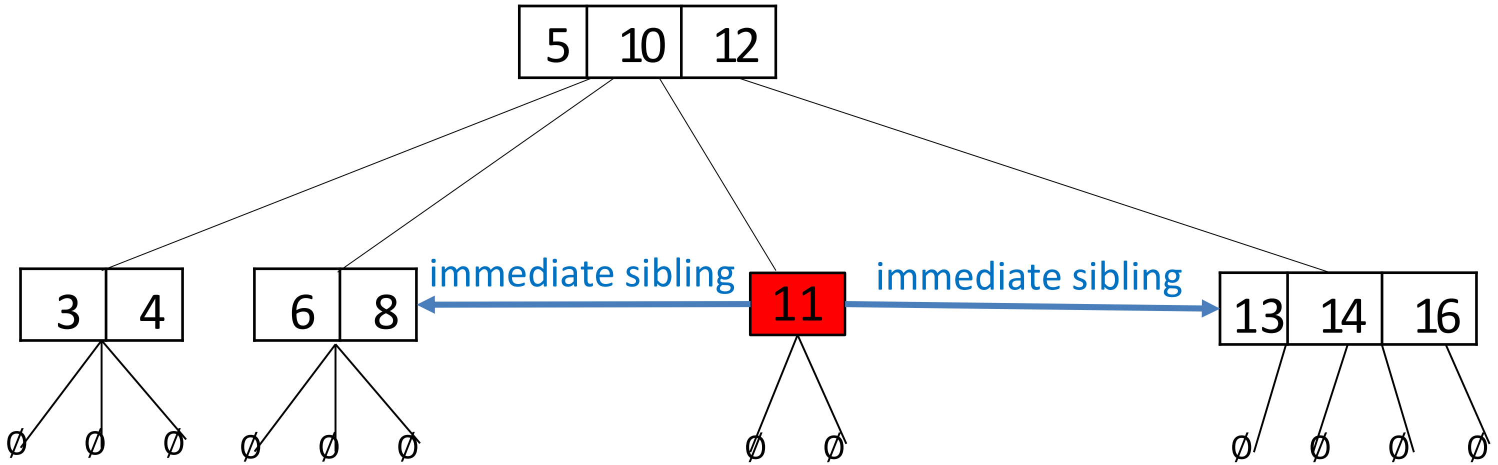
    replace $< v >$ by $< v', k_3, v'' >$ in key-subtree-list of p

    $v \leftarrow p$ //continue checking for overflow upwards

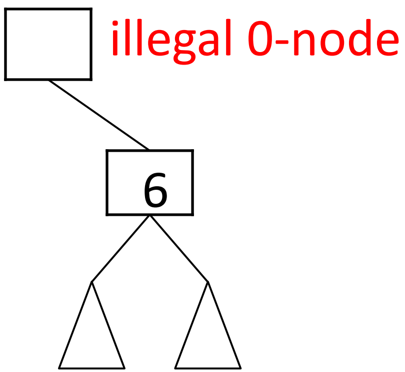


2-4 Tree: Immediate Sibling

- A node can have an *immediate* left sibling, immediate right sibling, or both

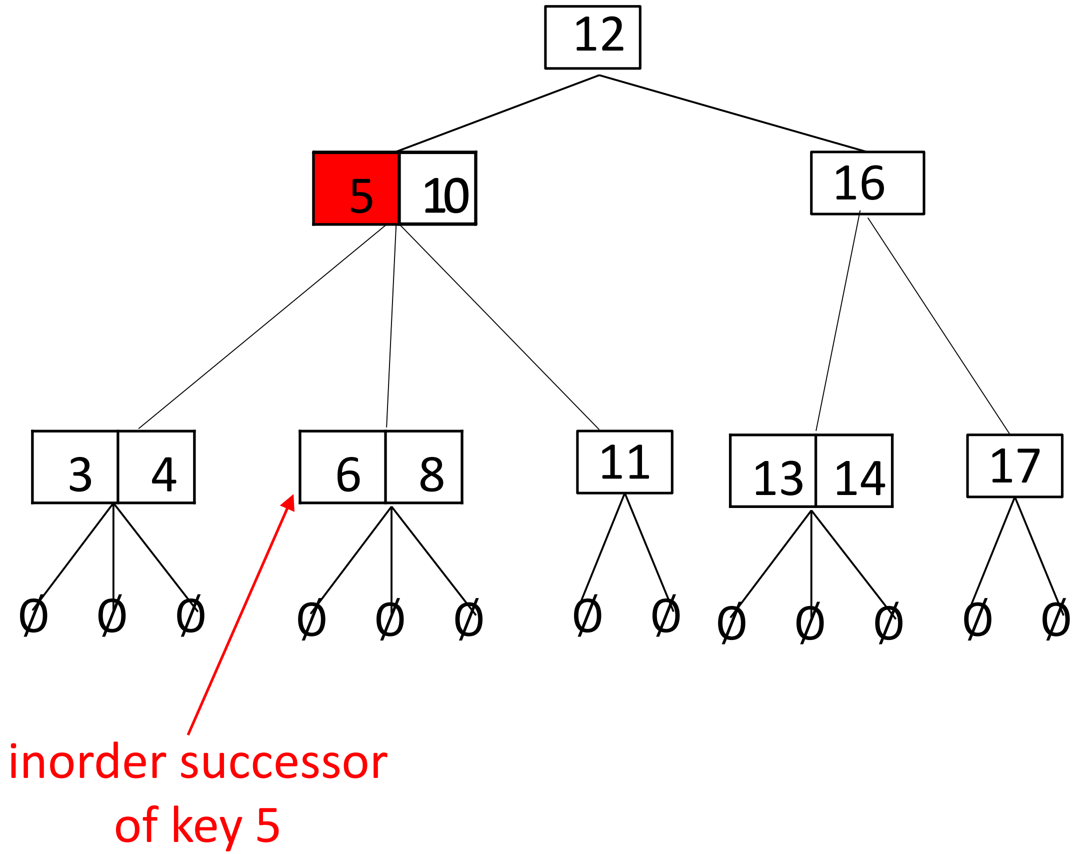


- Any node except the root must have an immediate sibling



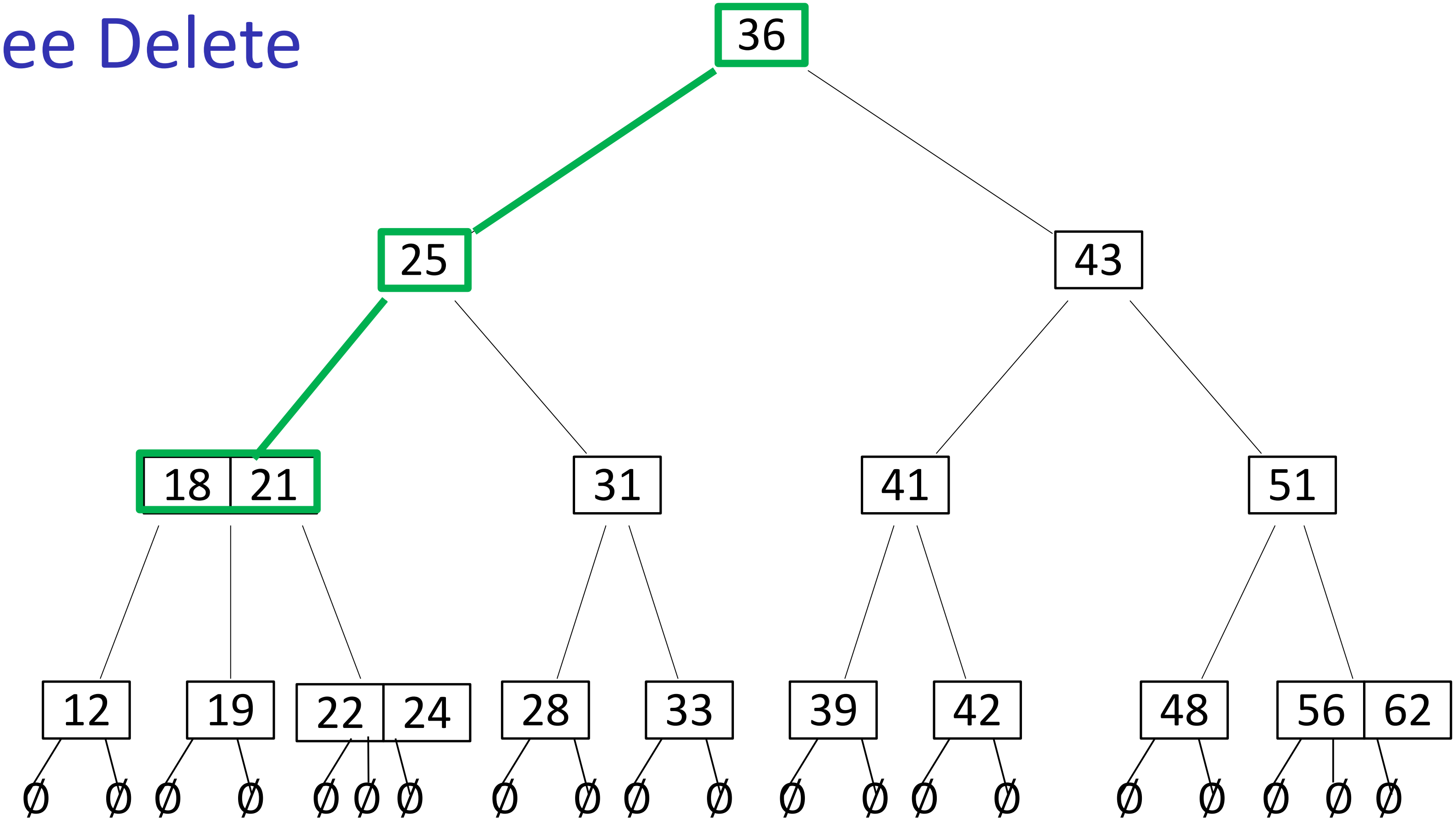
2-4 Tree: Inorder Successor

- Inorder successor of key k is the smallest key in the subtree immediately to the right of k



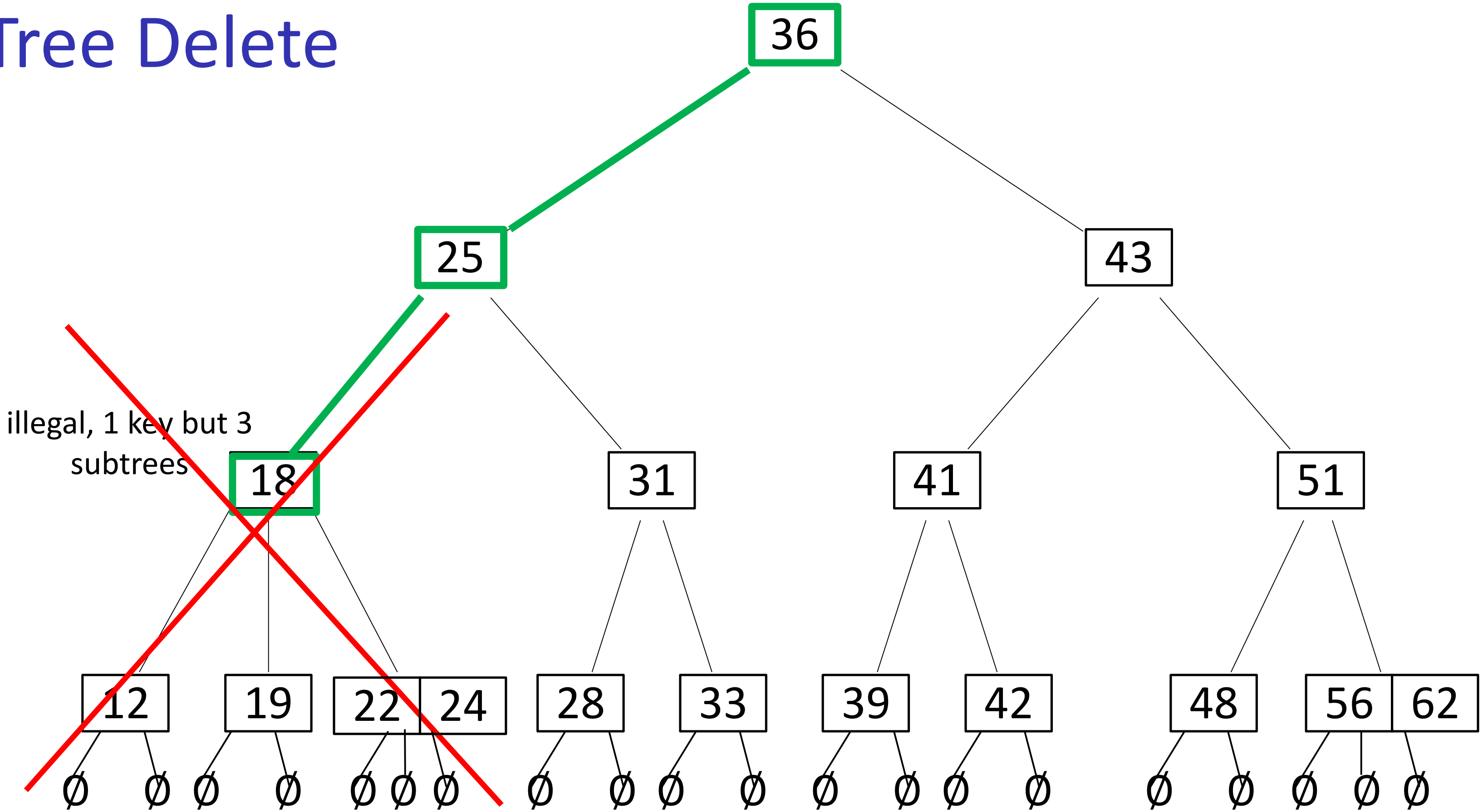
- Inorder successor is guaranteed to be at a leaf node
  - otherwise would have something smaller in the leftmost subtree

2-4 Tree Delete



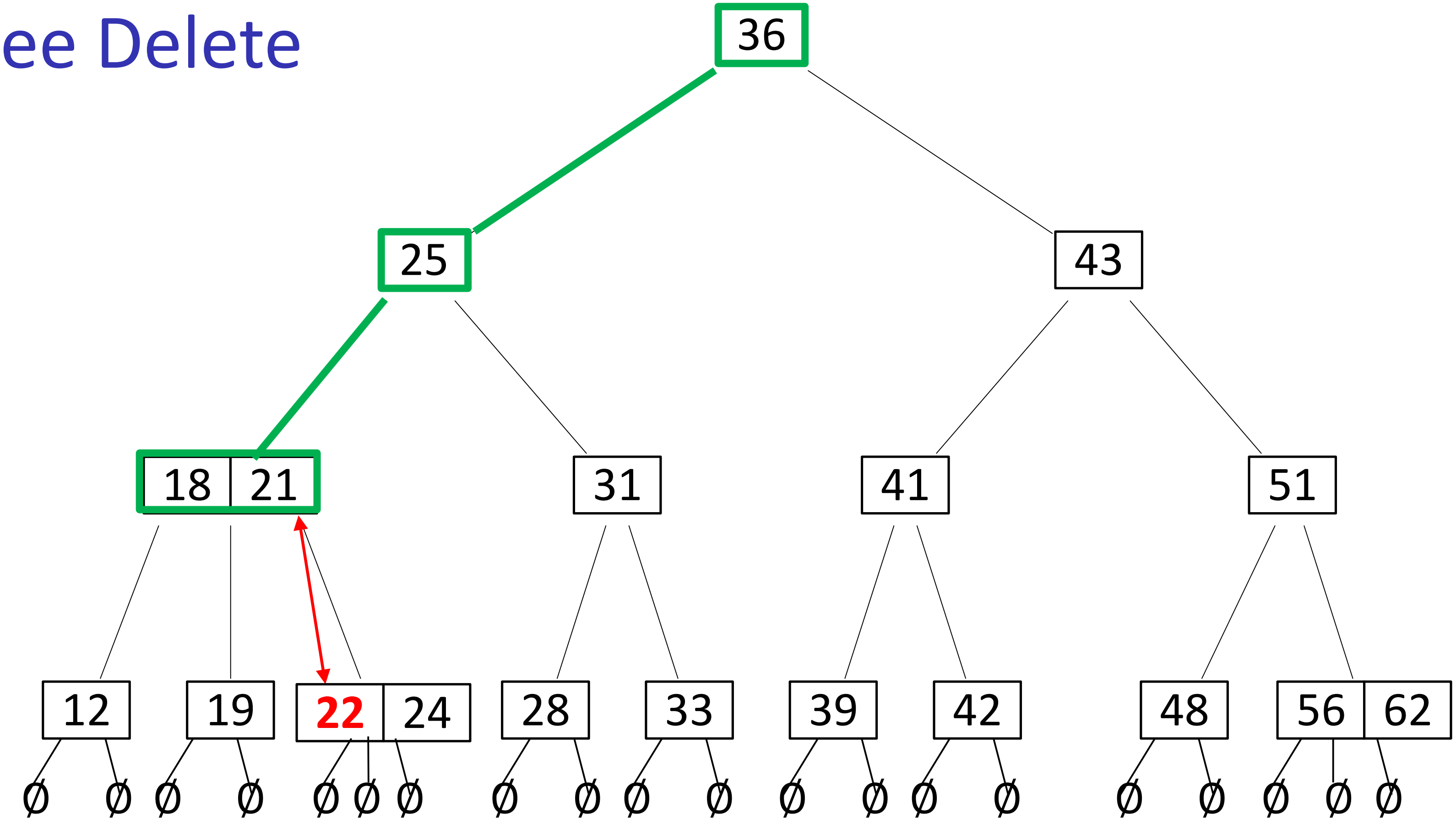
- Example: *delete*(21)
- Search for key to delete
  - if a node found has more than 1 key, it is tempting to delete it directly

2-4 Tree Delete



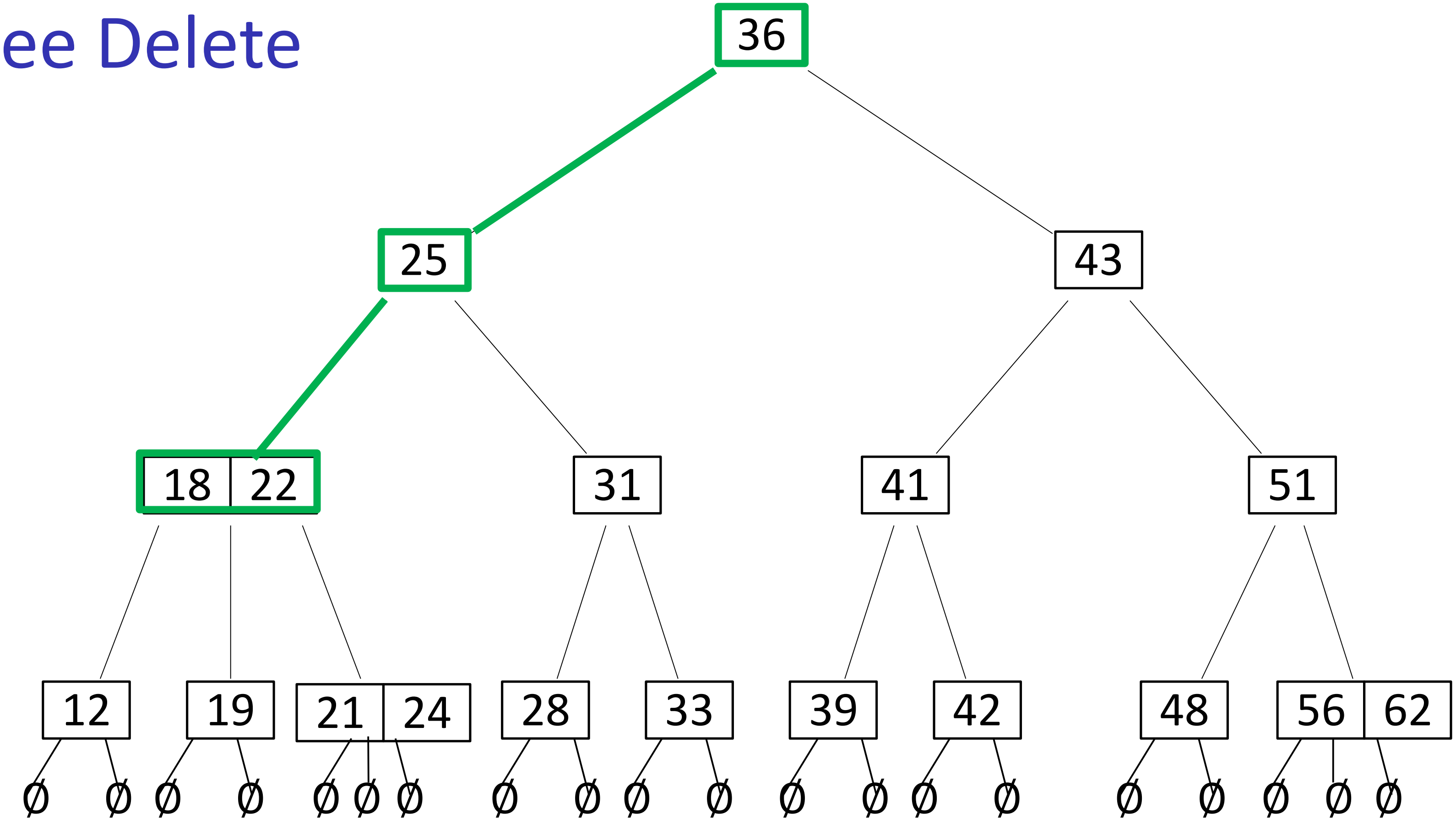
- Example: *delete*(21)
- Search for key to delete
  - if a node found has more than 1 key, it is tempting to delete it directly
  - however, can delete the key directly only if a node is a leaf
    - when we delete a key, we need to delete 1 subtree, easy only at a leaf

2-4 Tree Delete



- Example: *delete*(21)
- Search for key to delete
    - can delete keys only from a leaf node, as need to delete a subtree as well
    - if the key is in a node which is not a leaf, replace key with its inorder successor

2-4 Tree Delete



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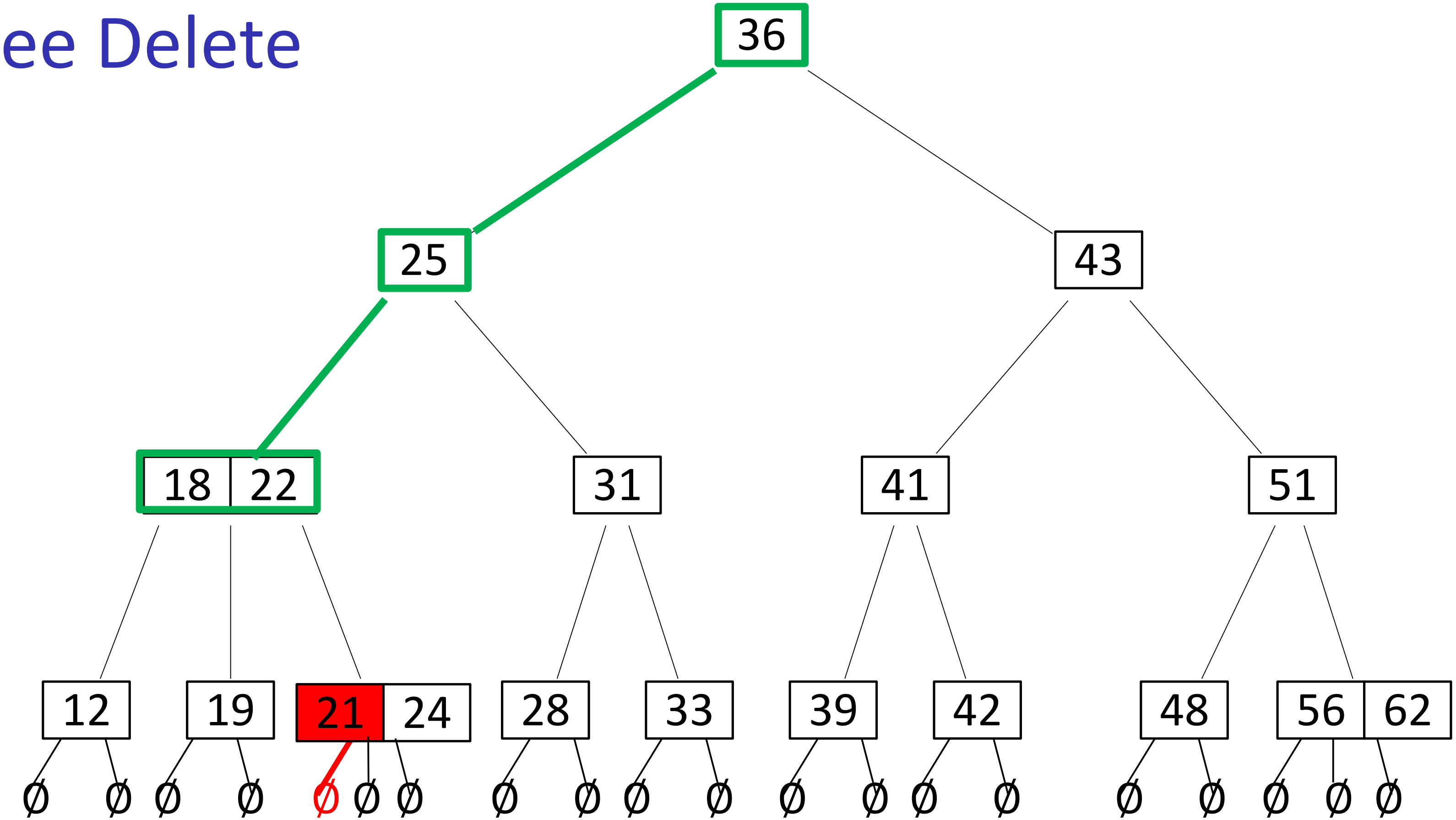
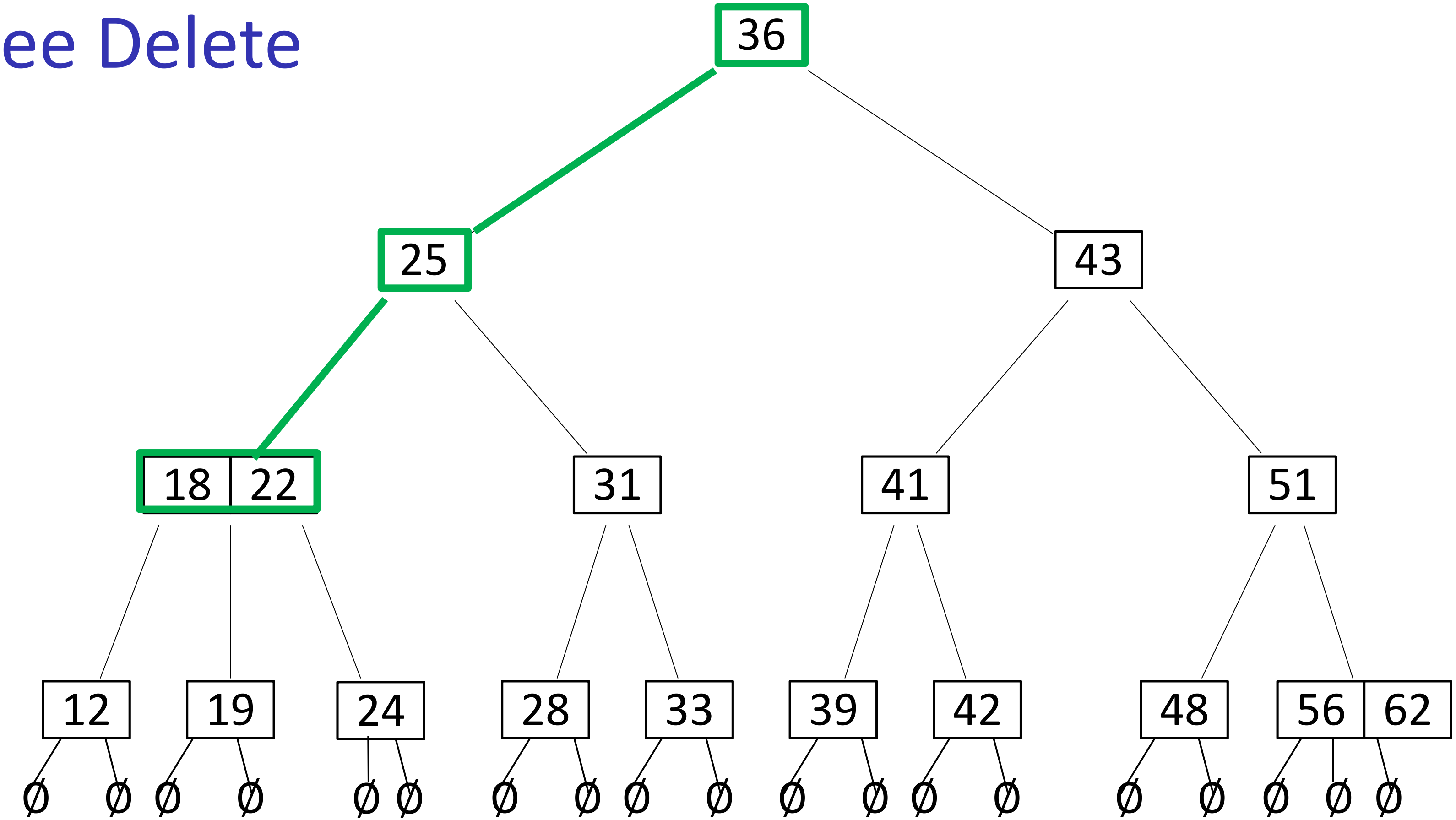
- Search for key to delete
  - can delete keys only from a leaf node, as need to delete a subtree as well
  - if the key is in a node which is not a leaf, replace key with its inorder successor

2-4 Tree Delete



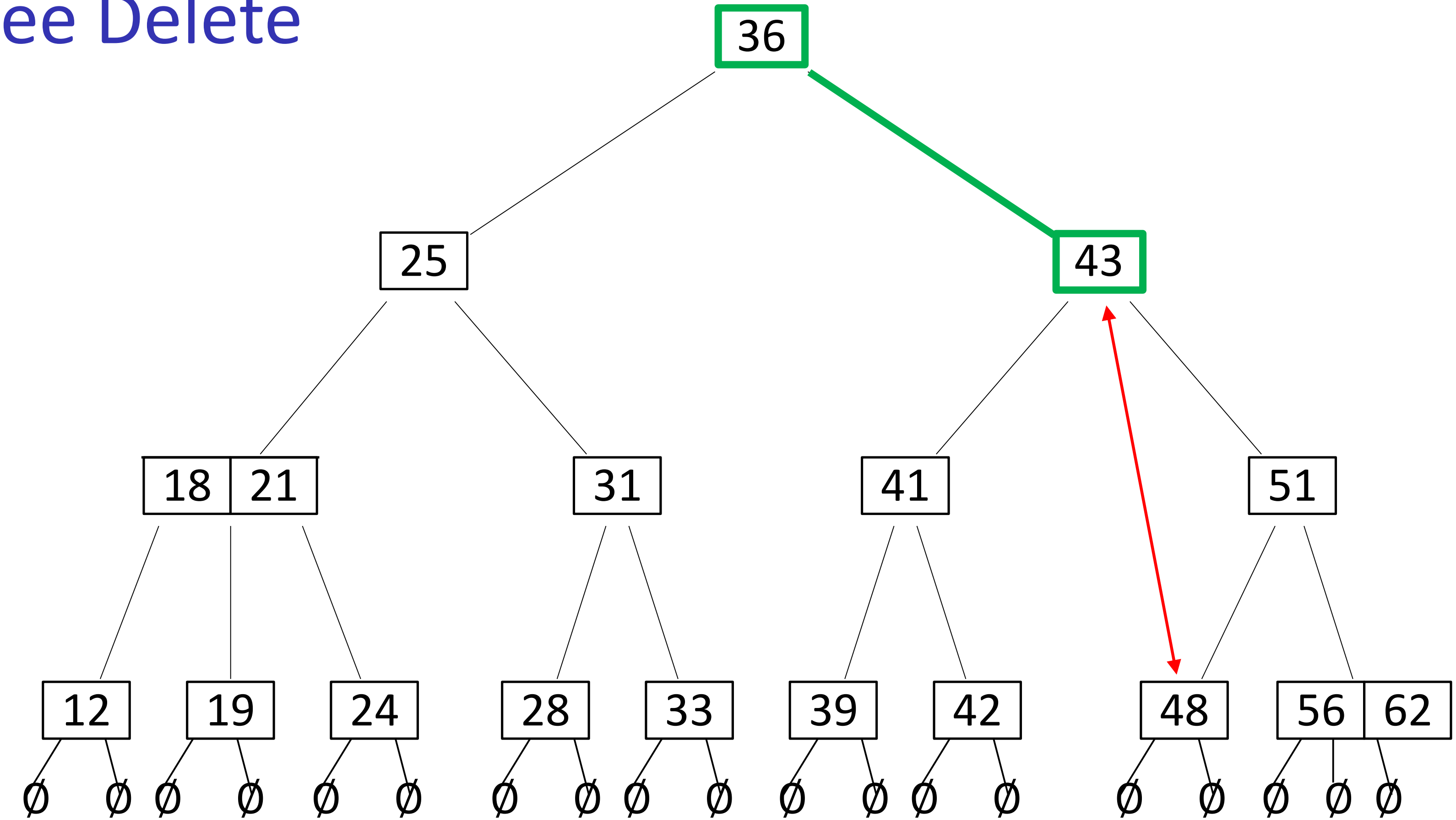
- Example: *delete*(21)
- Search for key to delete
    - can delete keys only from a leaf node, as need to delete a subtree as well
    - if the key is in a node which is not a leaf, replace key with its inorder successor
    - delete key 21 and an empty subtree

2-4 Tree Delete



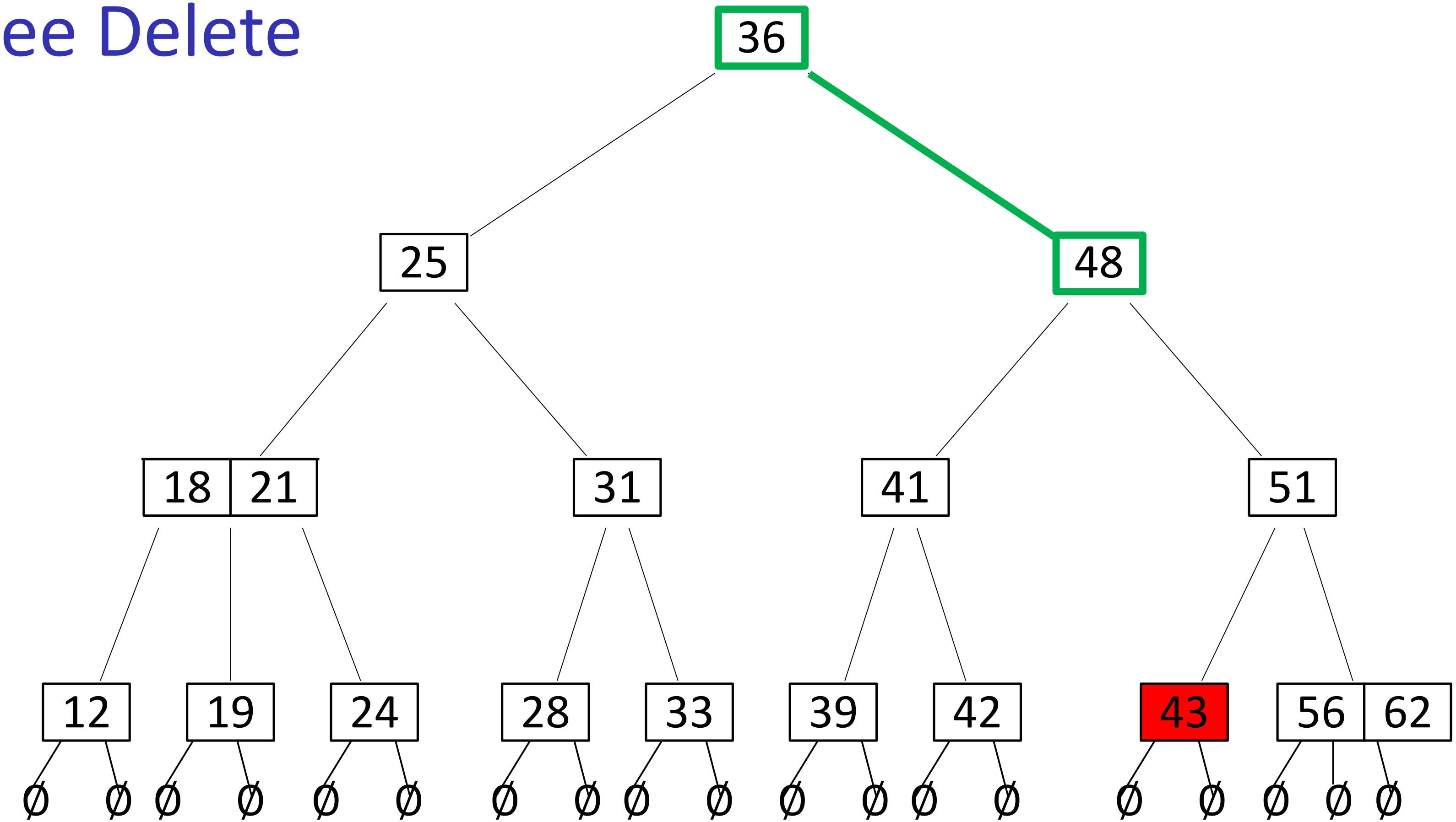
- Example: *delete*(21)
- Search for key to delete
  - can delete keys only from a leaf node, as need to delete a subtree as well
  - if the key is in a node which is not a leaf, replace key with its inorder successor
  - delete key 21 and an empty subtree
  - order property is preserved and we are done

2-4 Tree Delete



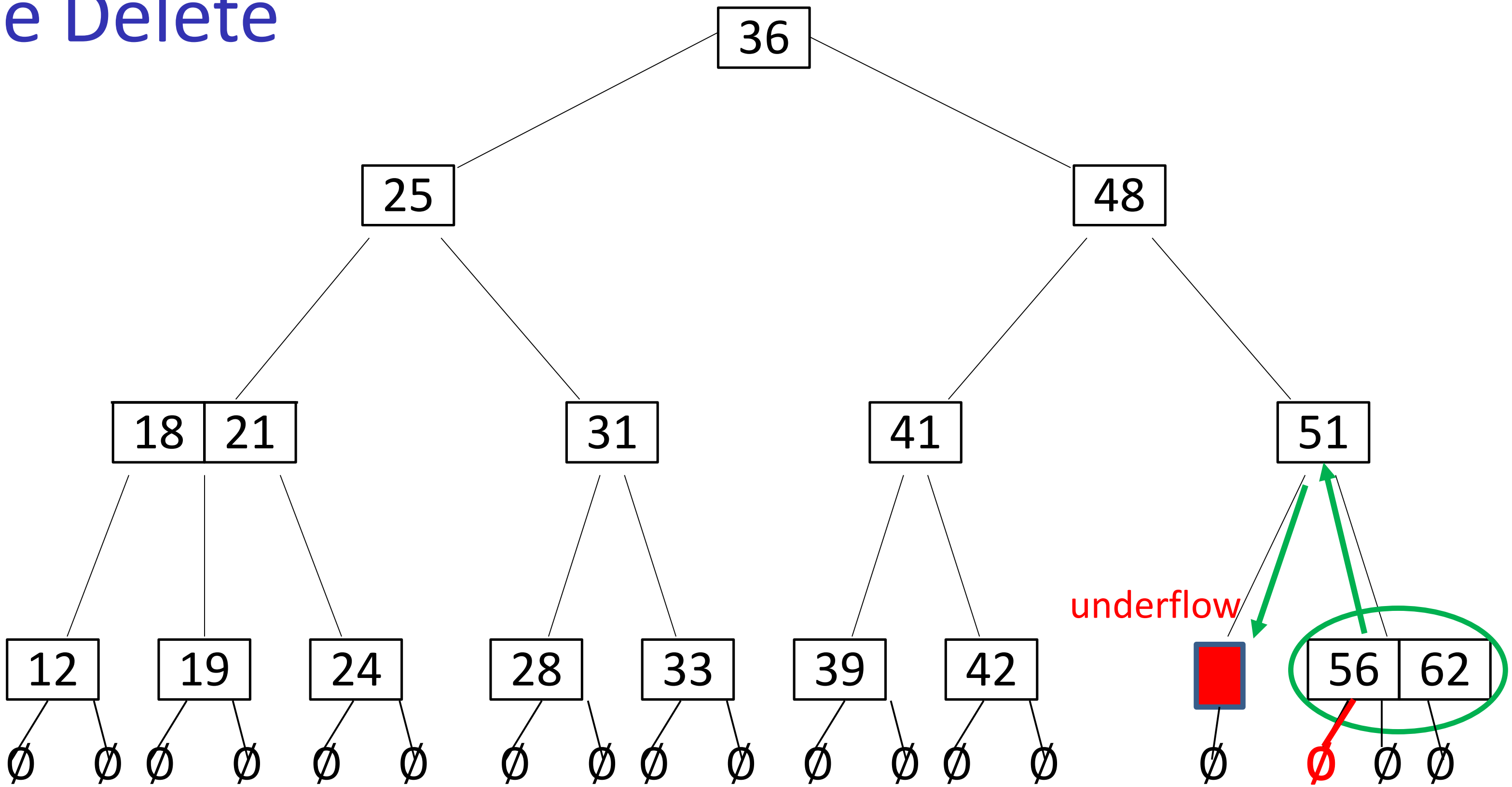
- Example: *delete*(43)
- Search for key to delete
    - can delete keys only from a leaf node
    - replace key with in-order successor

2-4 Tree Delete



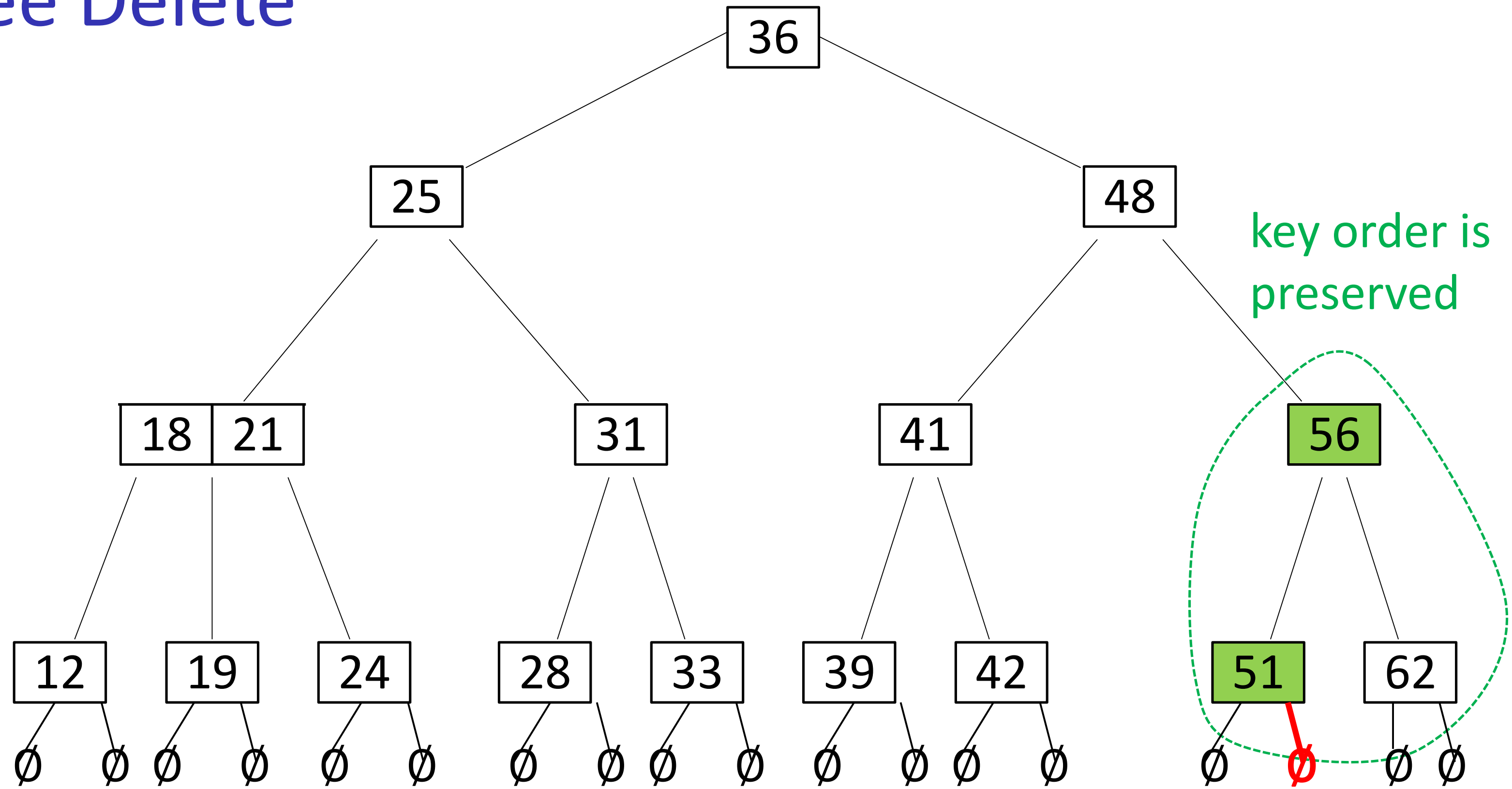
- Example: *delete*(43)
- Search for key to delete
  - can delete keys only from a leaf node
  - replace key with in-order successor
  - delete key 43 and a subtree

2-4 Tree Delete



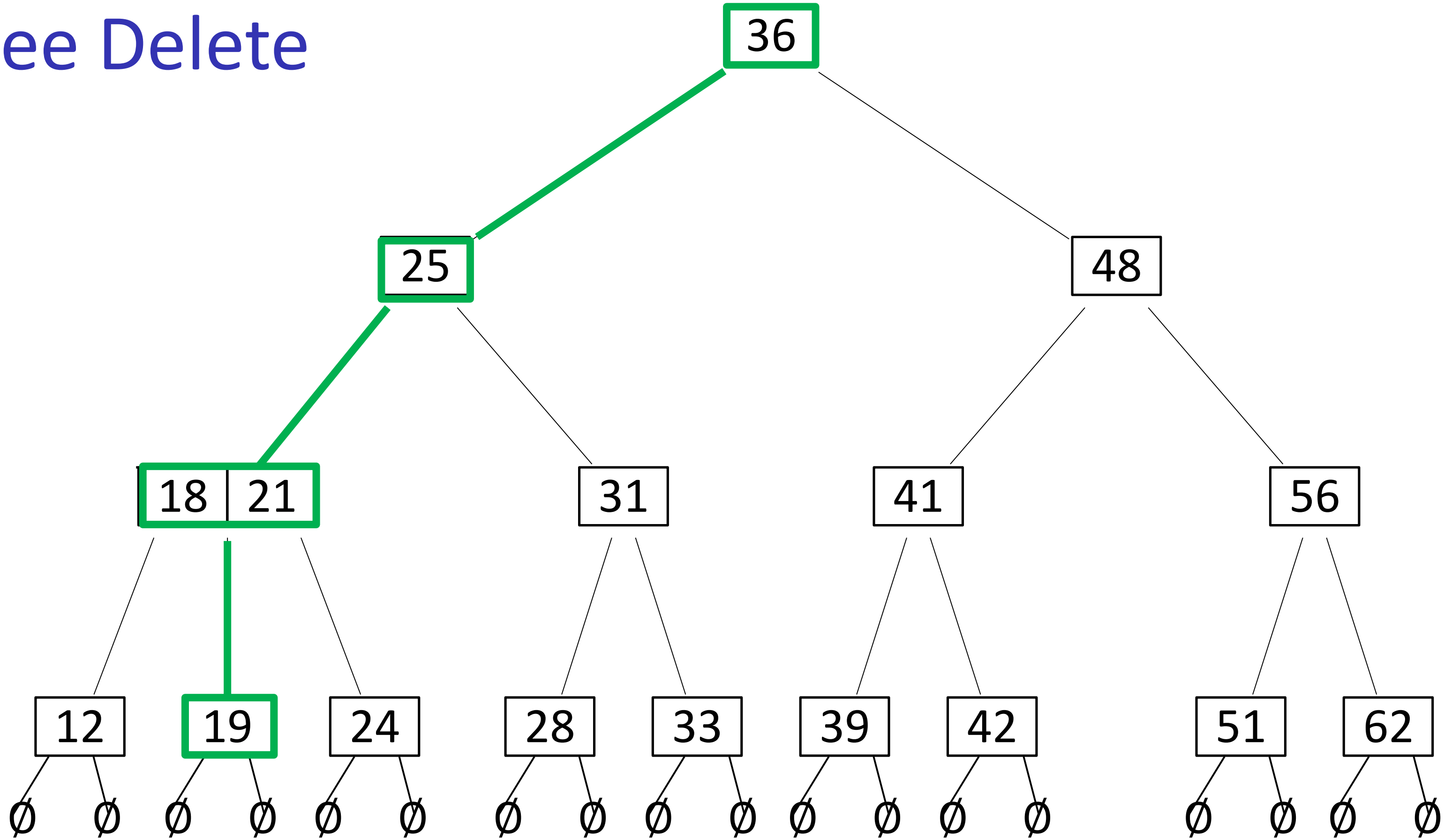
- Example: *delete*(43)
  - *rich* immediate sibling, transfer key from sibling, with help from the parent
    - sibling is *rich* if it is a 2-node or 3-node
    - adjacent subtree from sibling is also transferred

2-4 Tree Delete



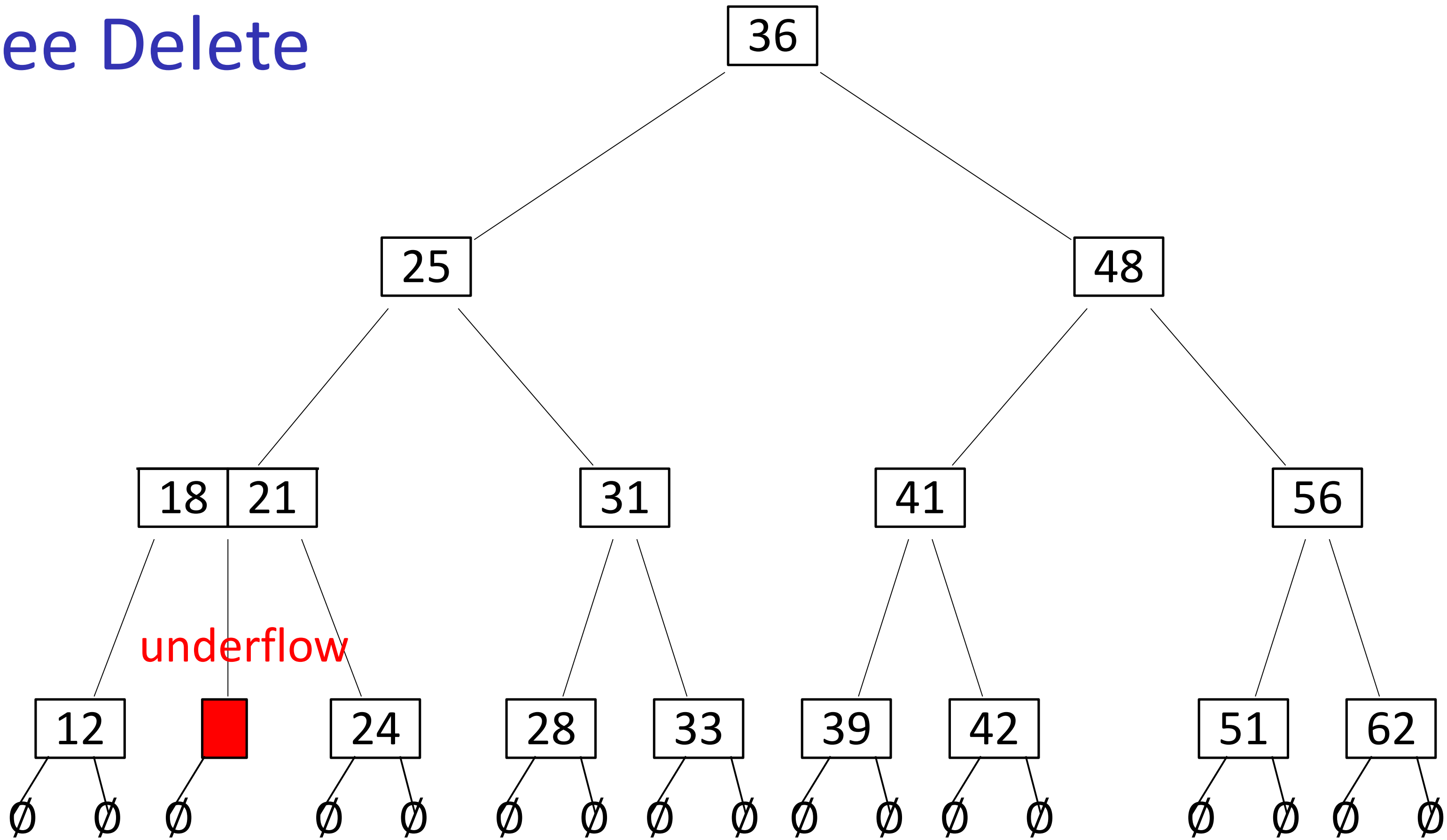
- Example: *delete*(43)
  - *rich* immediate sibling, transfer key from sibling, with help from the parent
    - sibling is *rich* if it is a 2-node or 3-node
    - adjacent subtree from sibling is also transferred
    - order property is preserved

2-4 Tree Delete



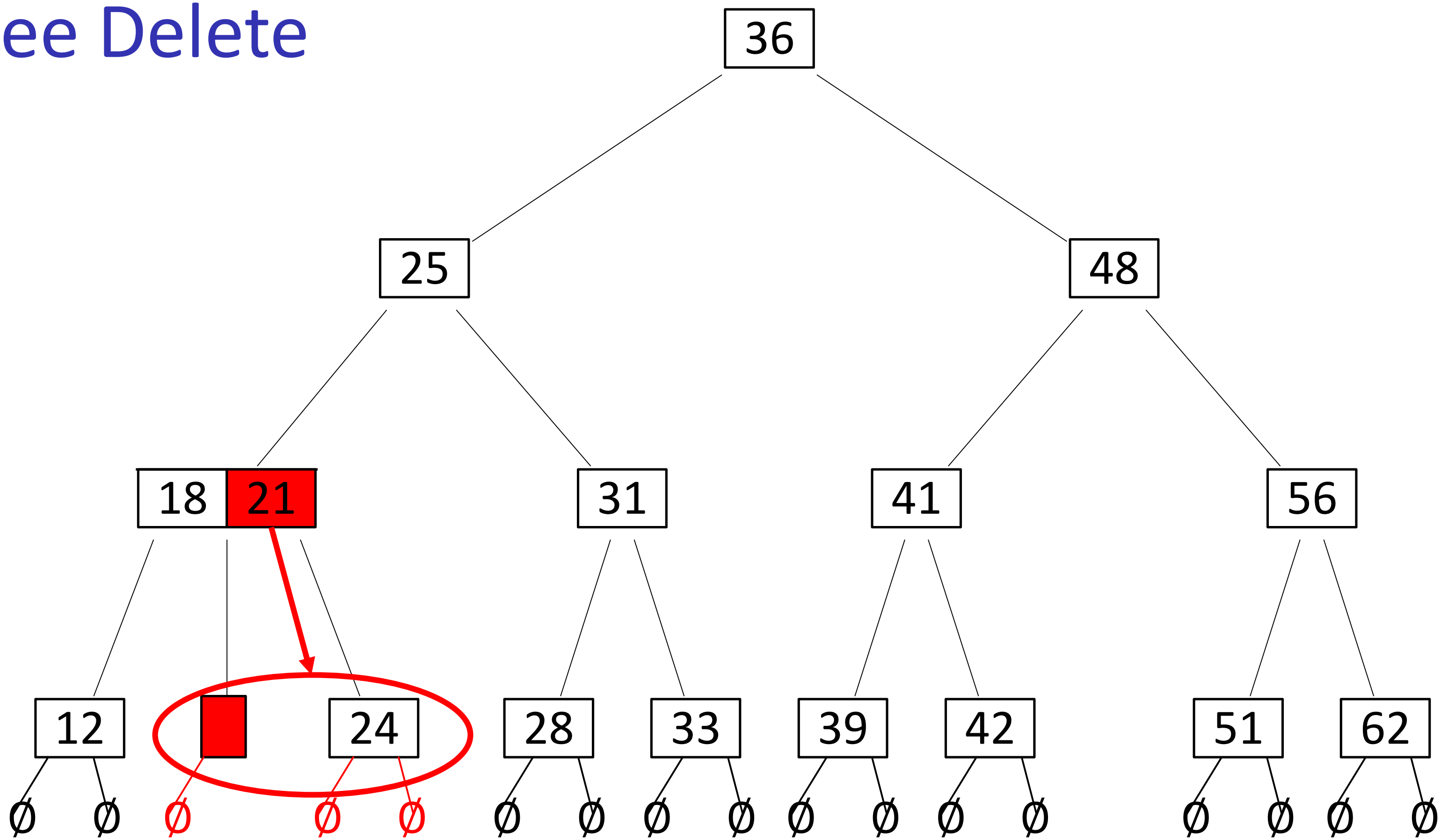
- Example: *delete*(19)
    - first search(19)

2-4 Tree Delete



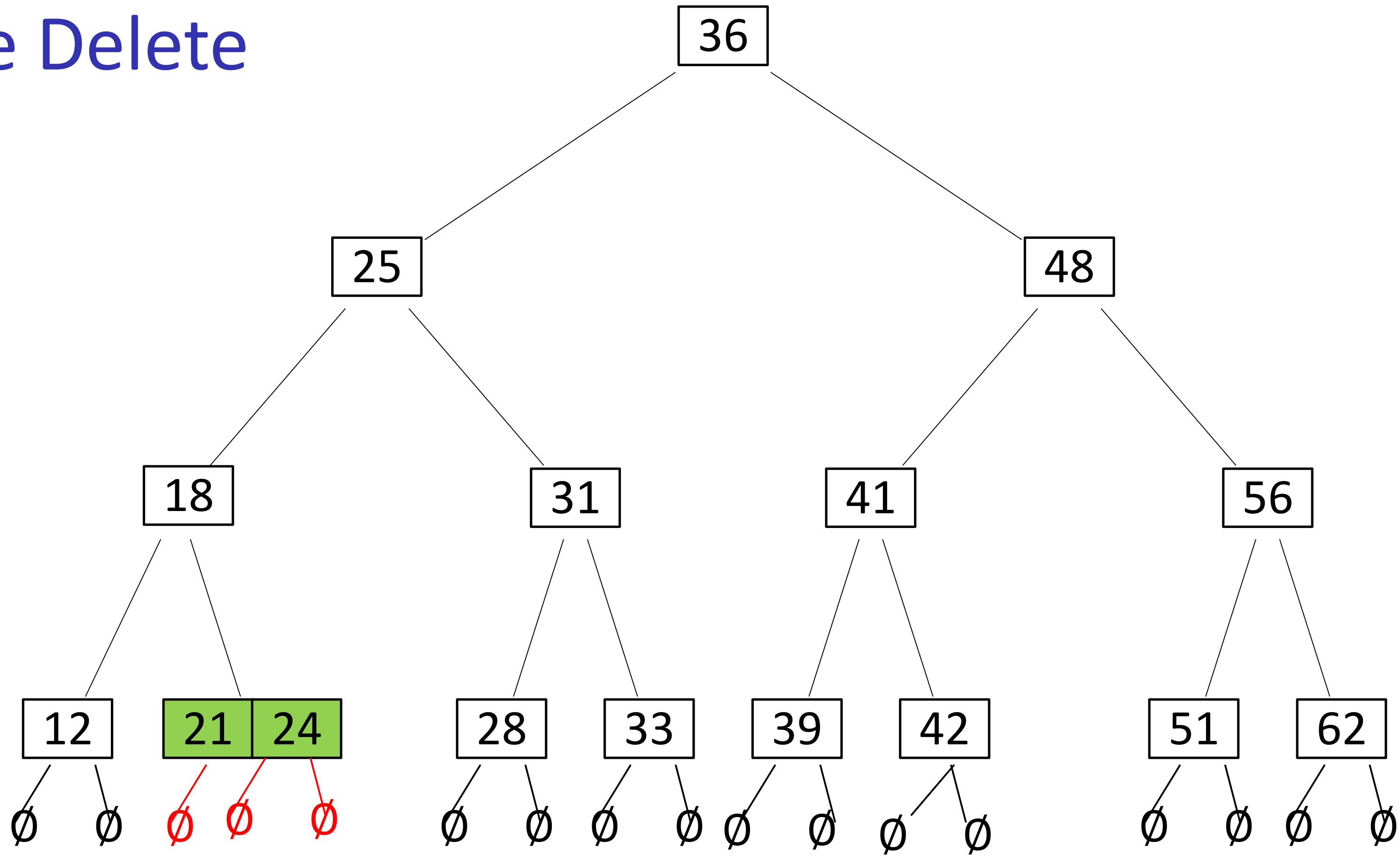
- Example: *delete*(19)
  - first search(19)
  - then delete key 19 (and an empty subtree) from the node
  - immediate siblings exist, but not rich, cannot transfer

2-4 Tree Delete



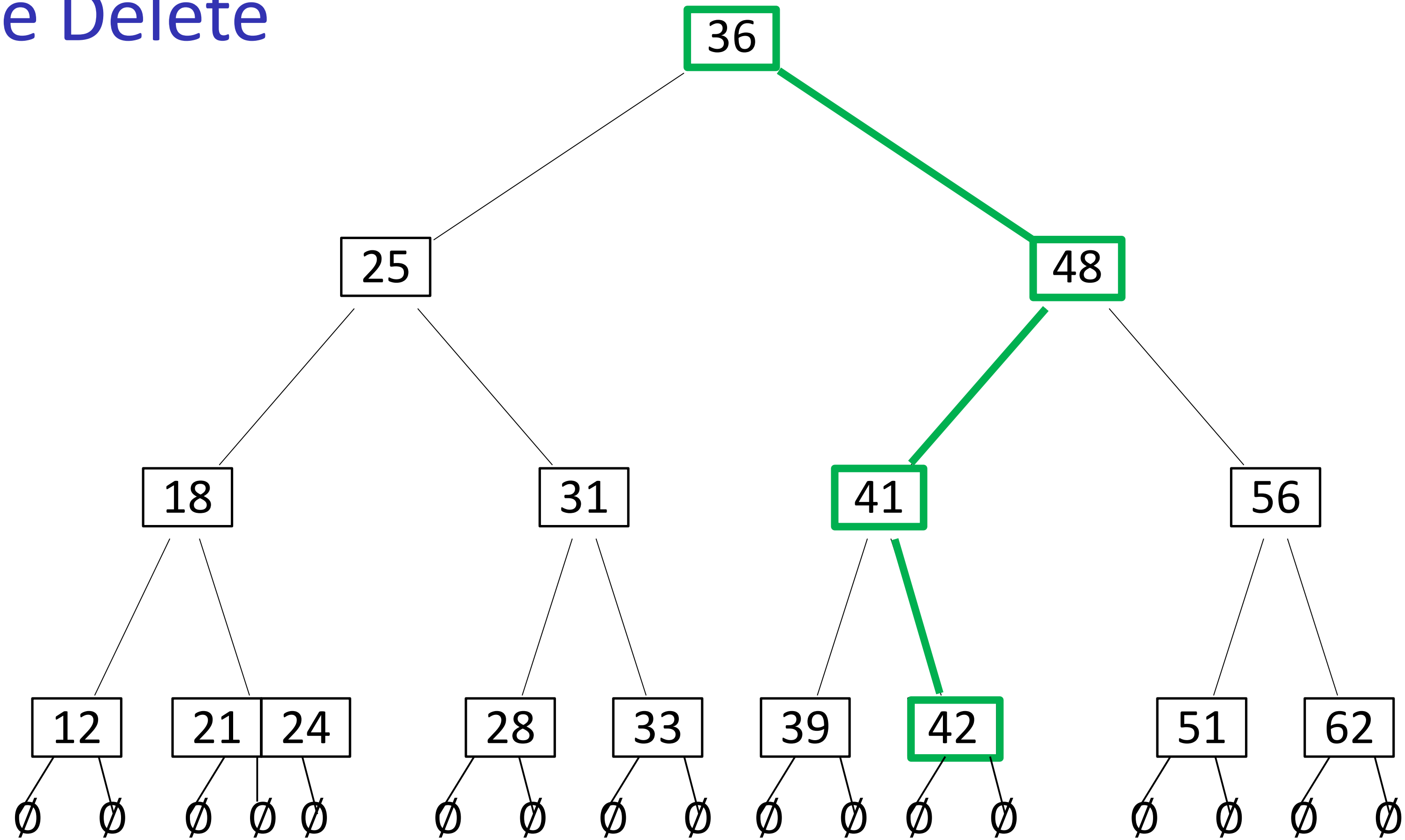
- Example: *delete*(19)
  - immediate siblings exist, but not rich, cannot transfer
    - merge with right immediate sibling with help from parent

2-4 Tree Delete



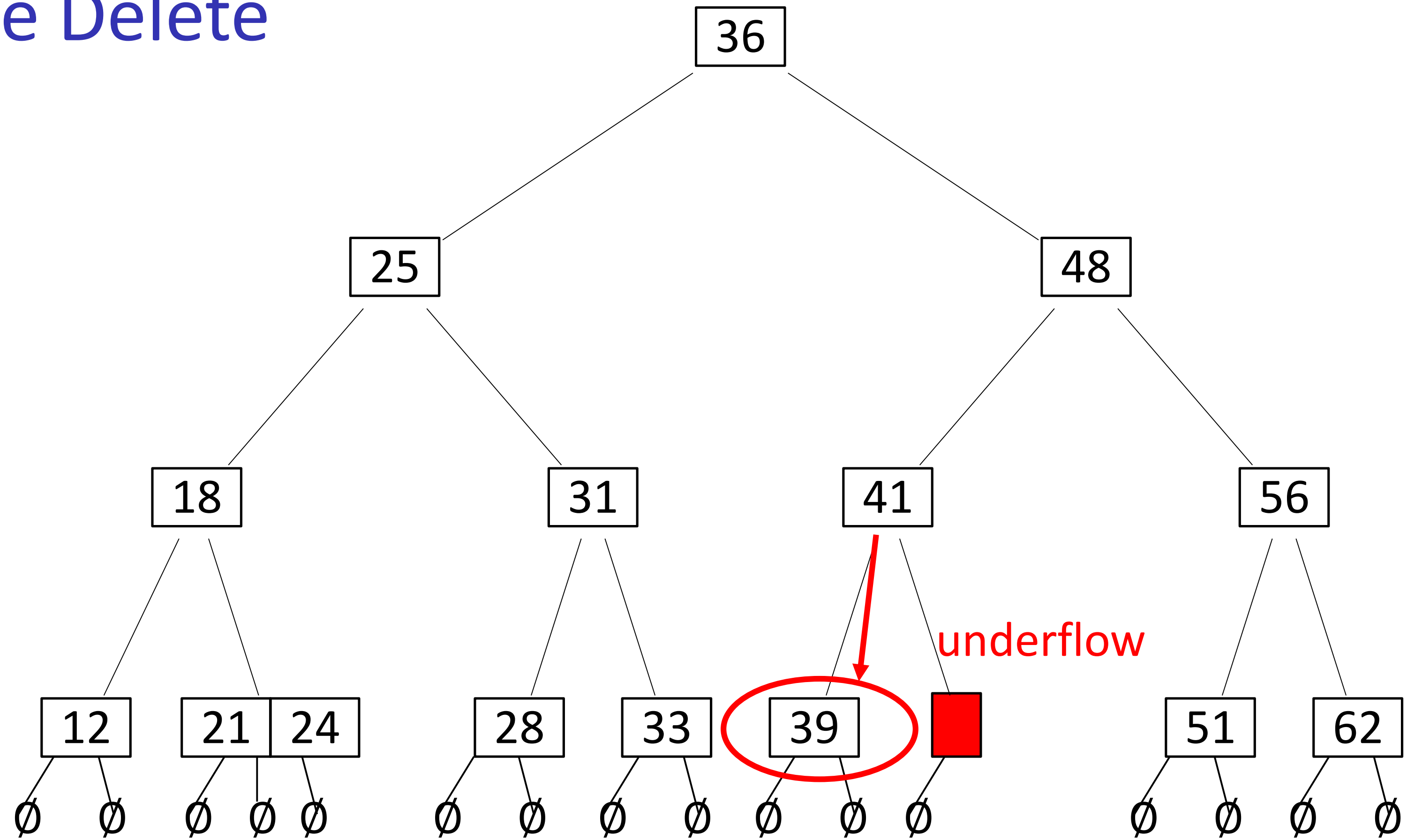
- Example: *delete*(19)
  - immediate siblings exist, but not rich, cannot transfer
    - merge with right immediate sibling with help from parent
      - all subtrees merged together as well
  - structural and order properties are preserved

2-4 Tree Delete



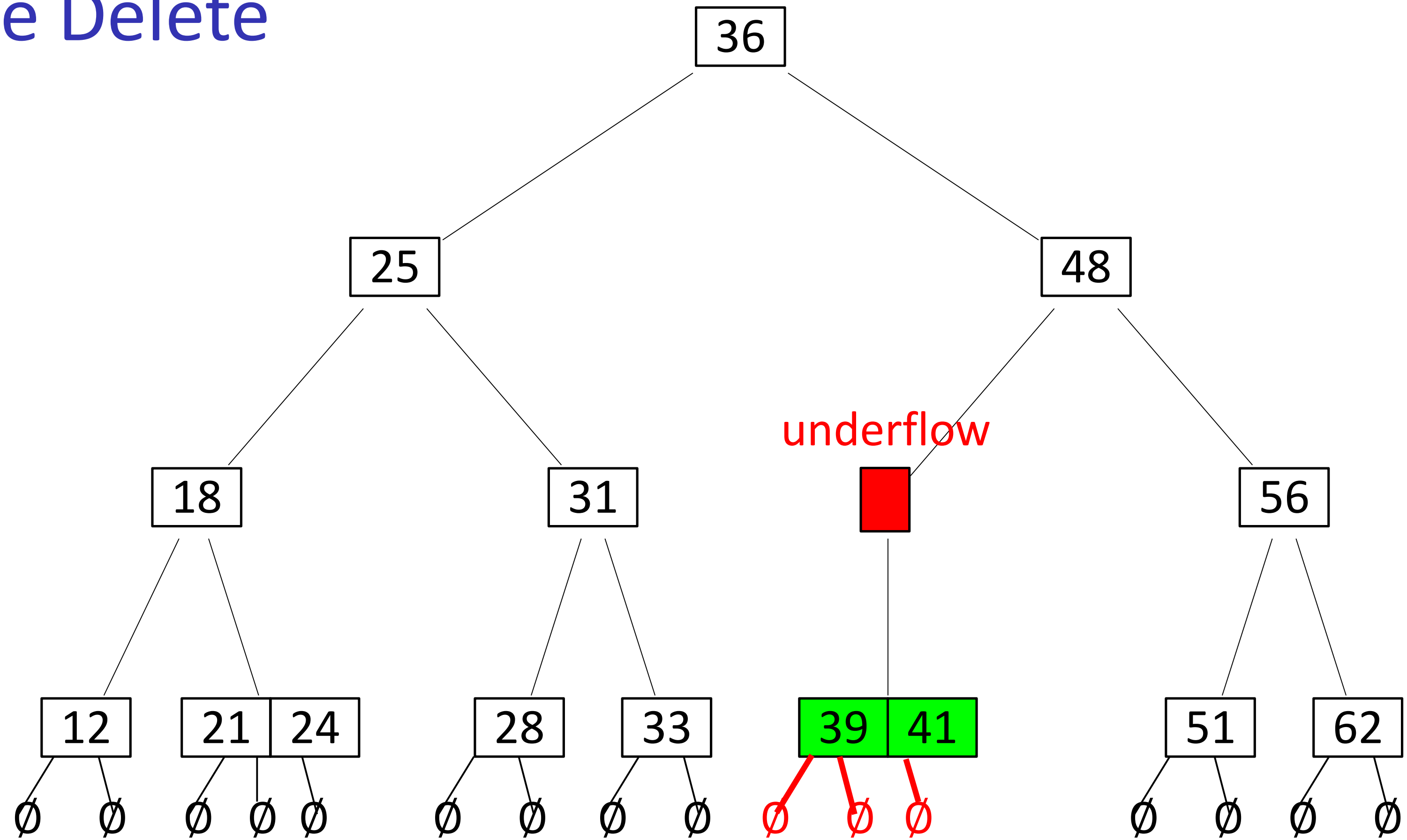
- Example: *delete*(42)
    - first search(42)
    - delete key 42 with one empty subtree

2-4 Tree Delete



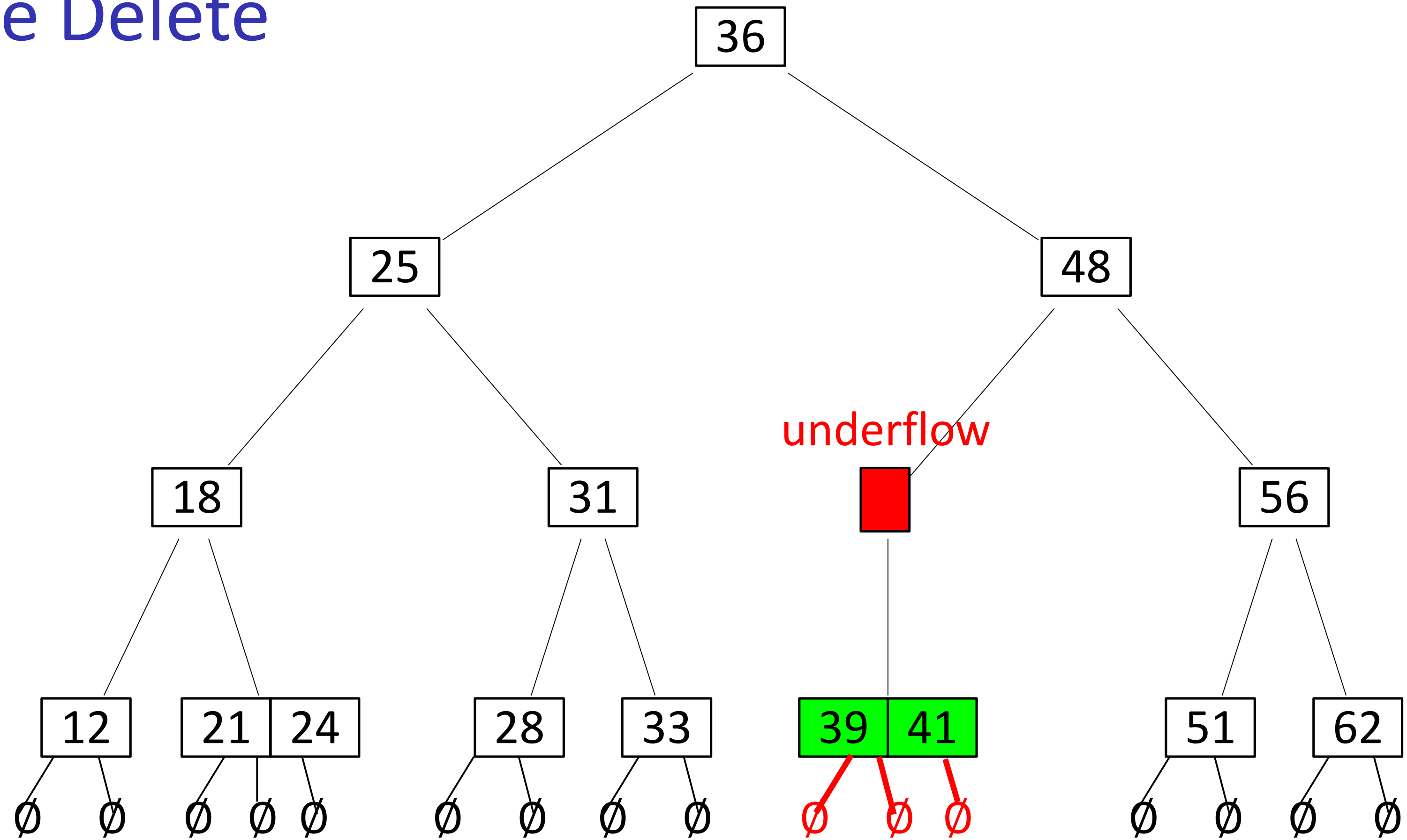
- Example: *delete*(42)
    - first search(42)
    - the only immediate sibling is not rich, perform merge

2-4 Tree Delete



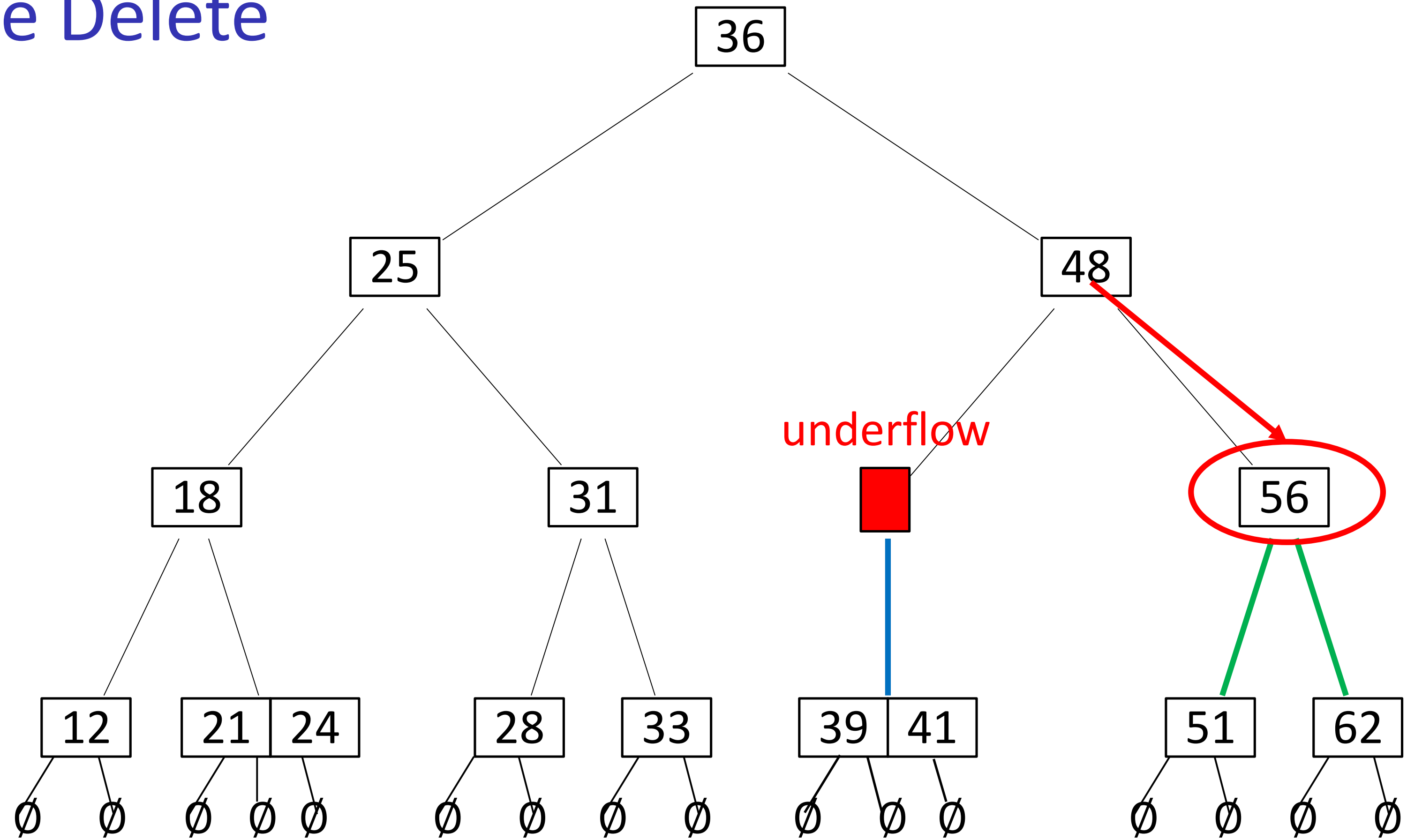
- Example: *delete*(42)
  - first search(42)
  - the only immediate sibling is not rich, perform merge
    - all subtrees merged together as well

2-4 Tree Delete



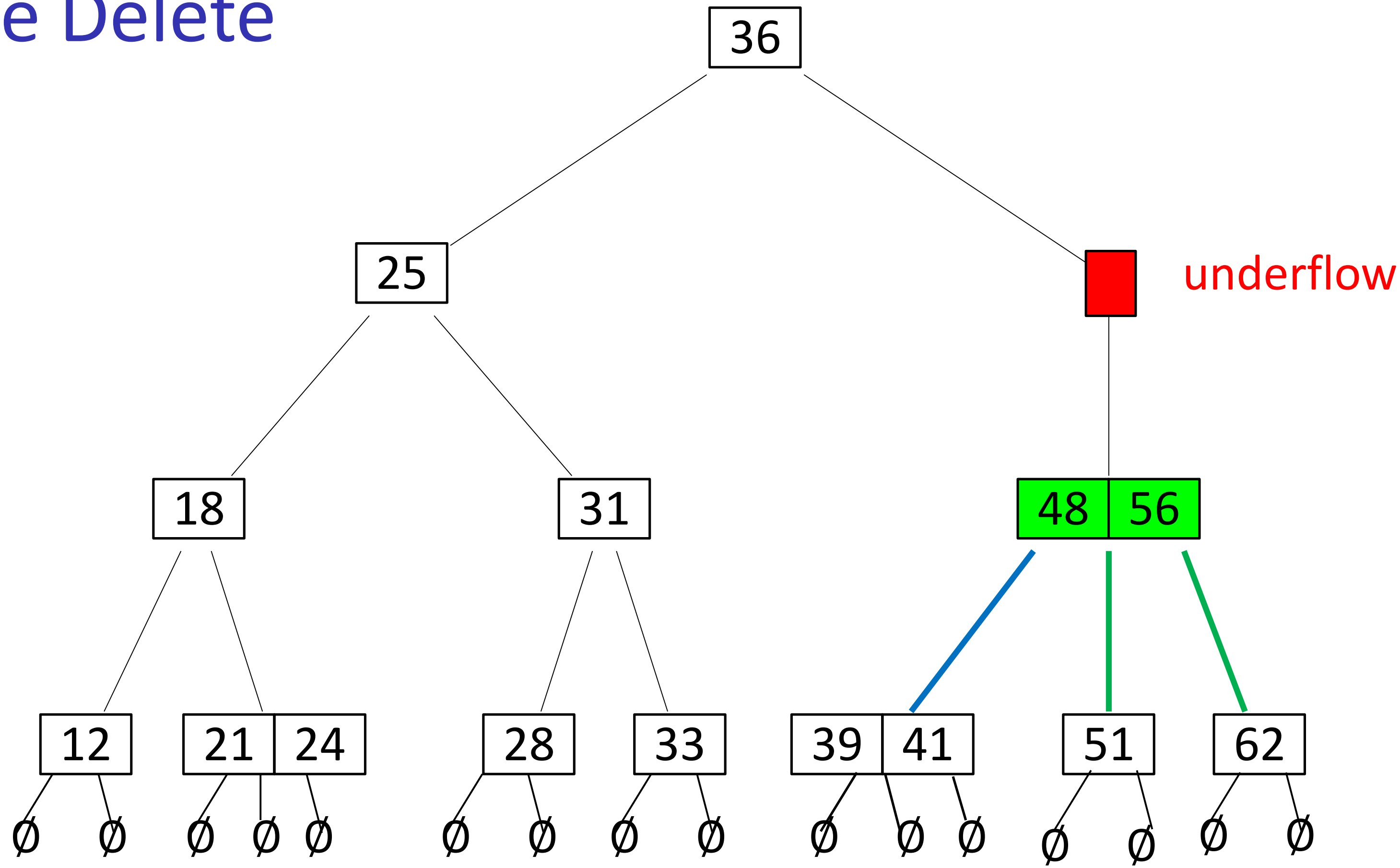
- Example: *delete*(42)
  - merge operation can cause underflow at the parent node
  - while needed, continue fixing the tree upwards
    - possibly all the way to the root

2-4 Tree Delete



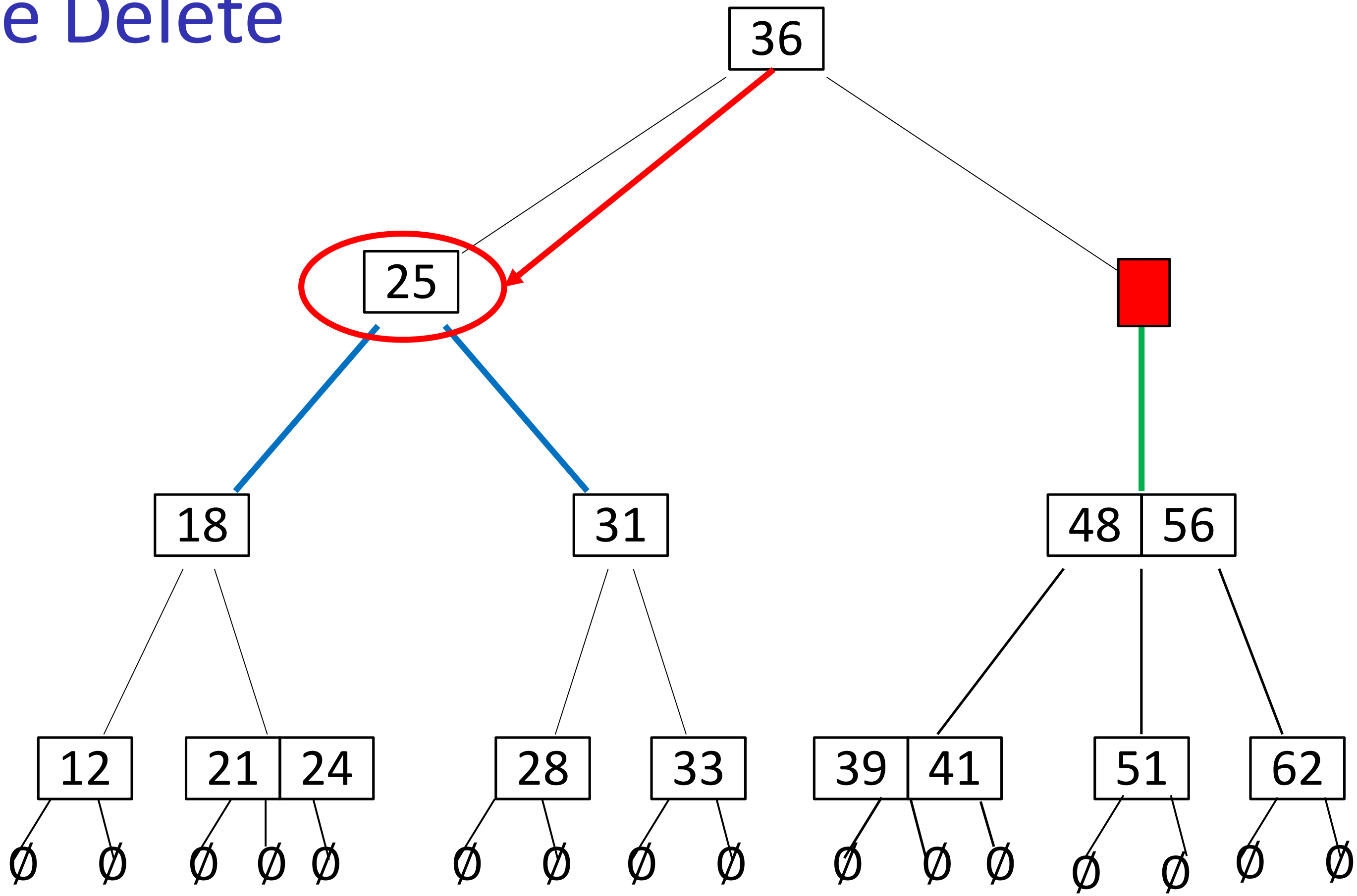
- Example: *delete*(42)
    - the only sibling is not rich, perform a merge

2-4 Tree Delete



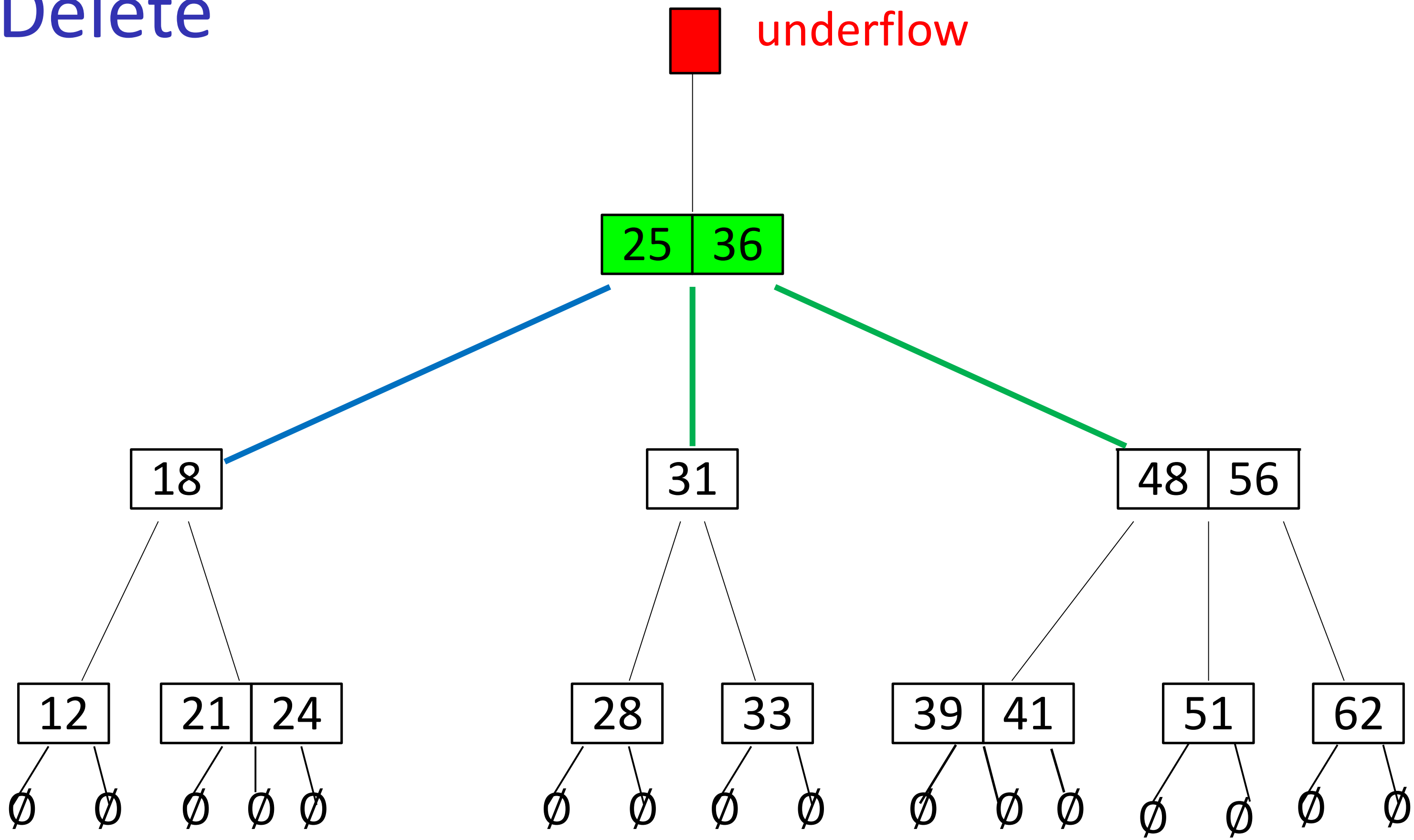
- Example: *delete*(42)
  - the only sibling is not rich, perform a merge
  - subtrees are merged as well
  - continue fixing the tree upwards

2-4 Tree Delete



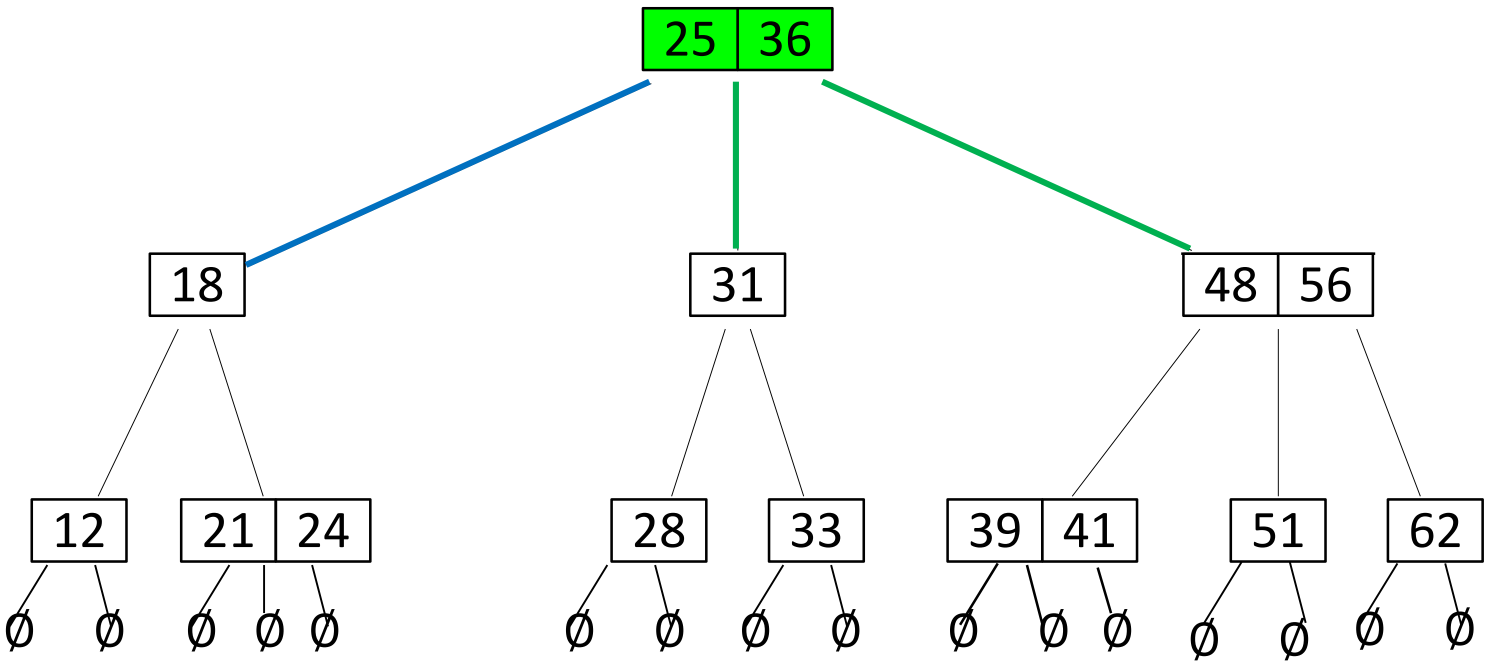
- Example: *delete*(42)
  - the only sibling is not rich, perform a merge

2-4 Tree Delete



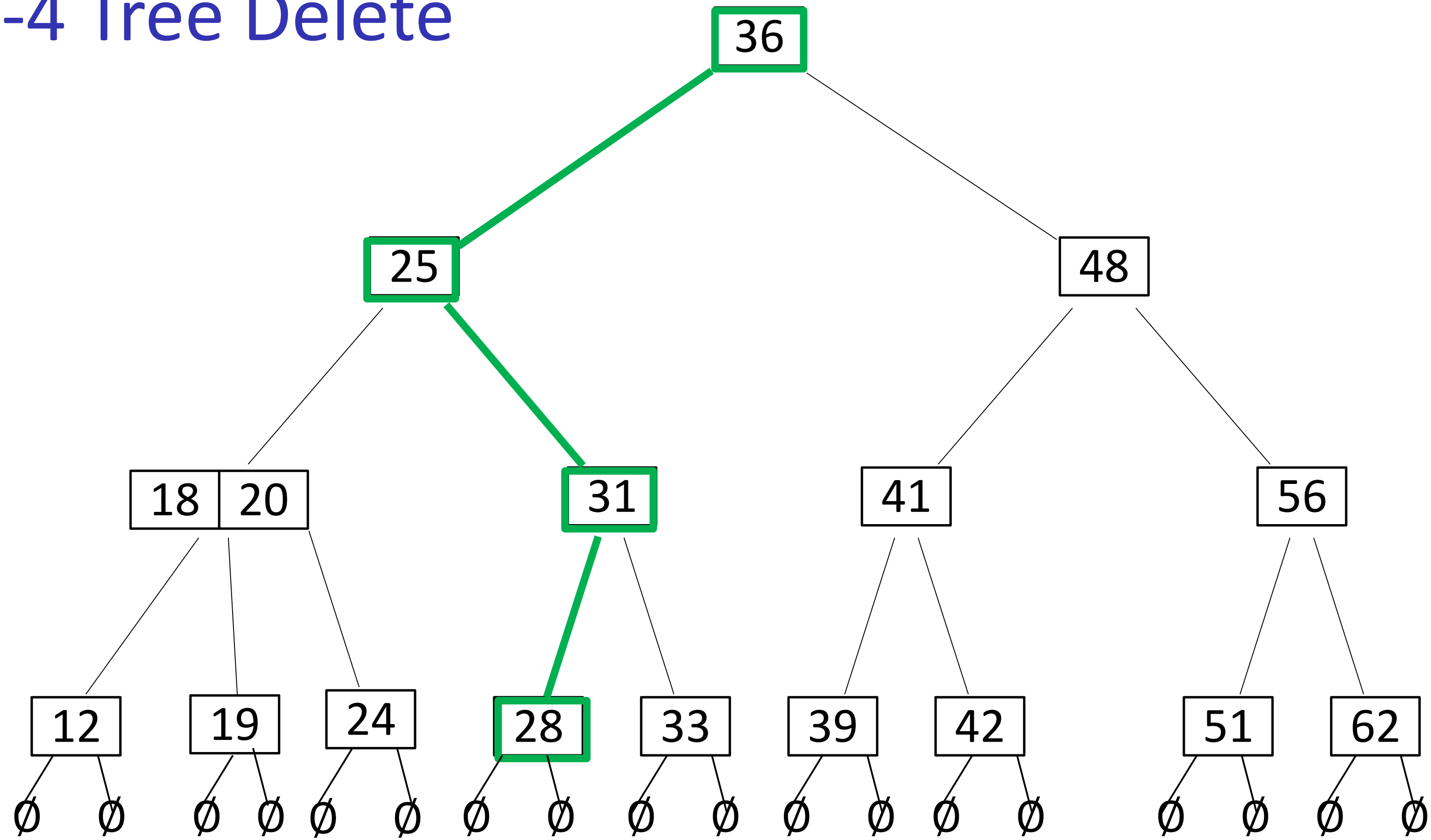
- Example: *delete*(42)
  - the only sibling is not rich, perform merge
  - underflow at parent node
    - it is the root, delete root

2-4 Tree Delete



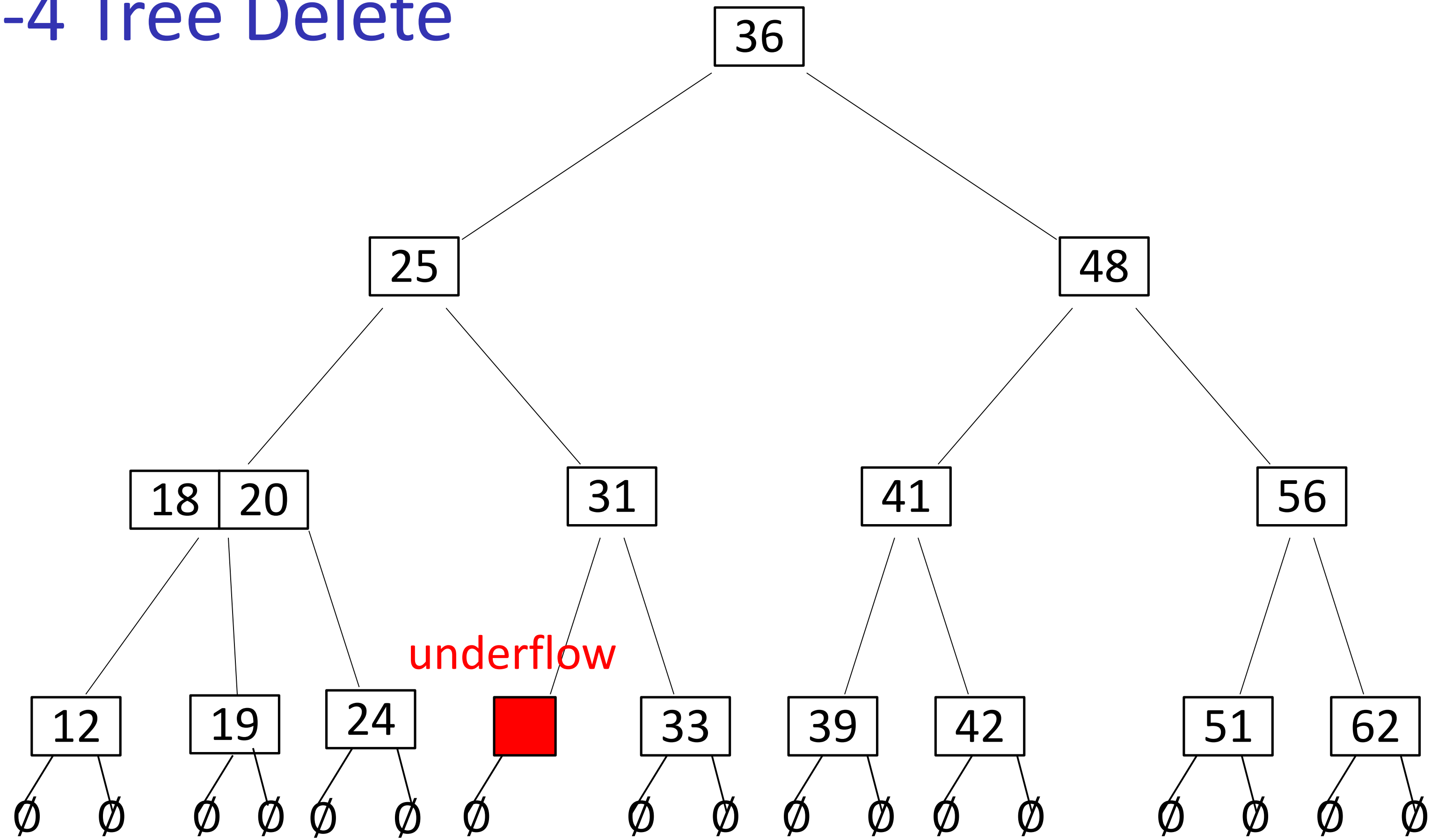
- Example: *delete*(42)
  - the only sibling is not rich, perform merge
  - underflow at parent node
    - it is the root, delete root

2-4 Tree Delete



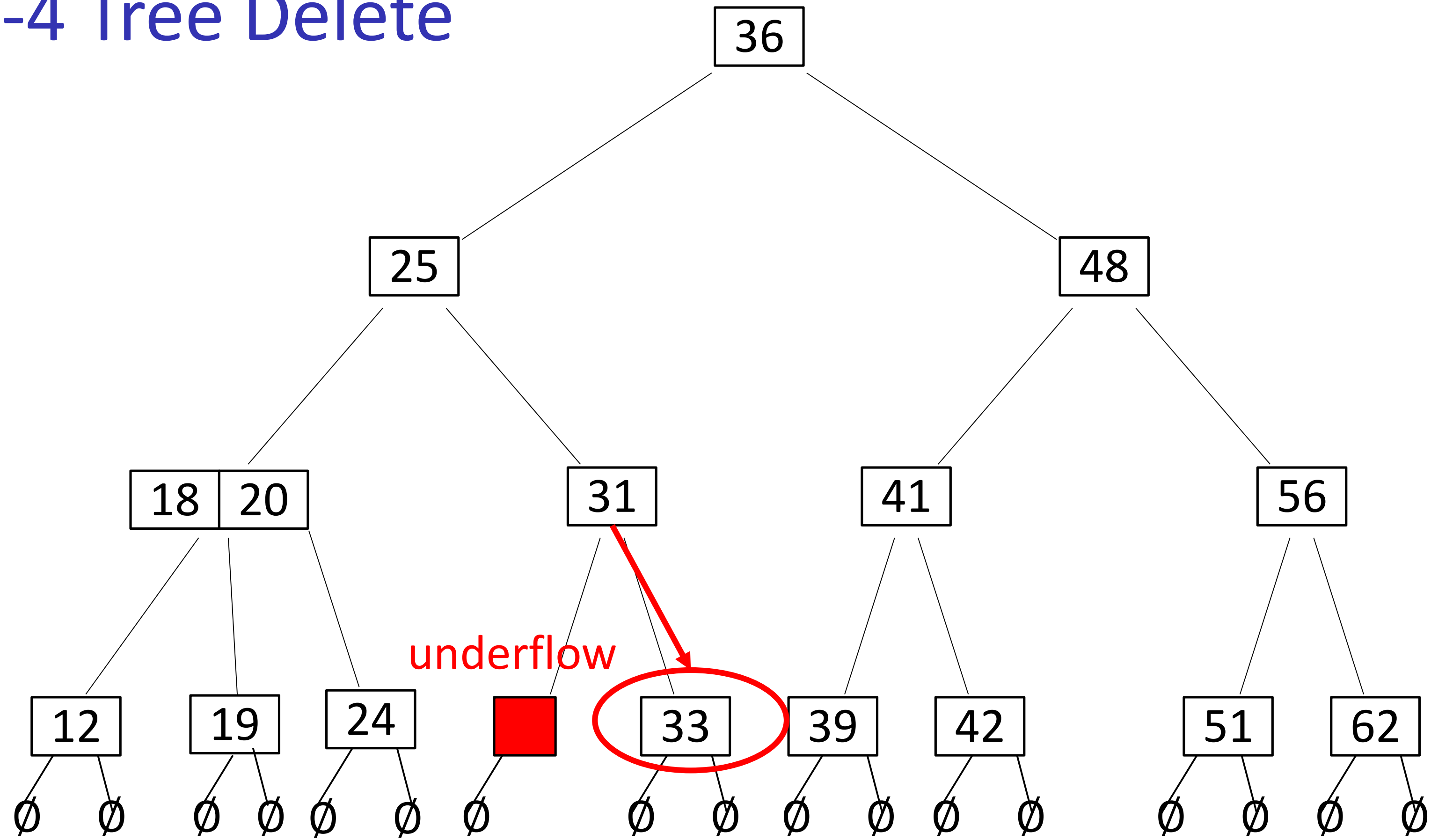
- Example: *delete*(28)
    - first search(28)
    - delete key 28 with one empty subtree

2-4 Tree Delete



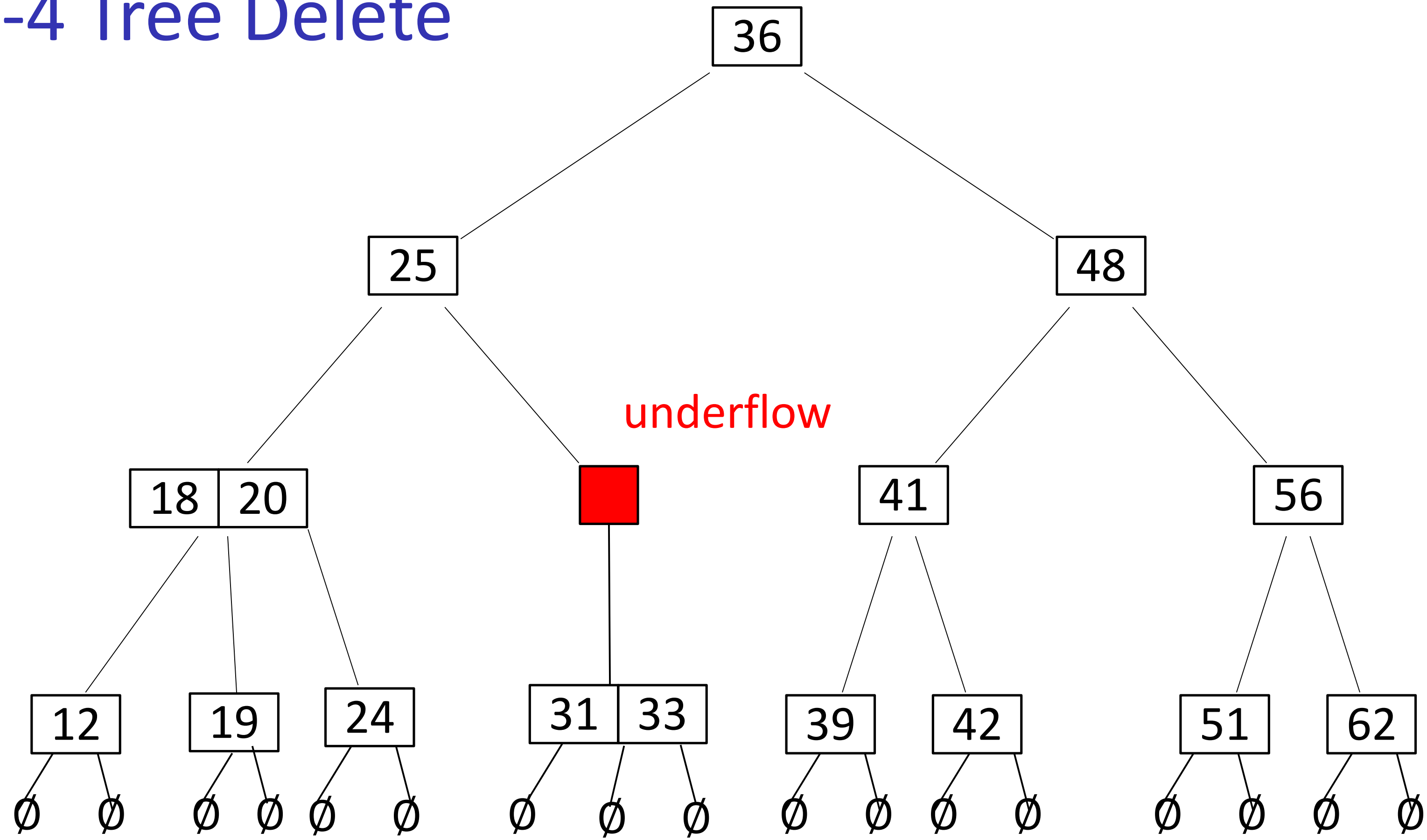
- Example: *delete*(28)
  - first search(28)
  - delete key 28 with one empty subtree

2-4 Tree Delete



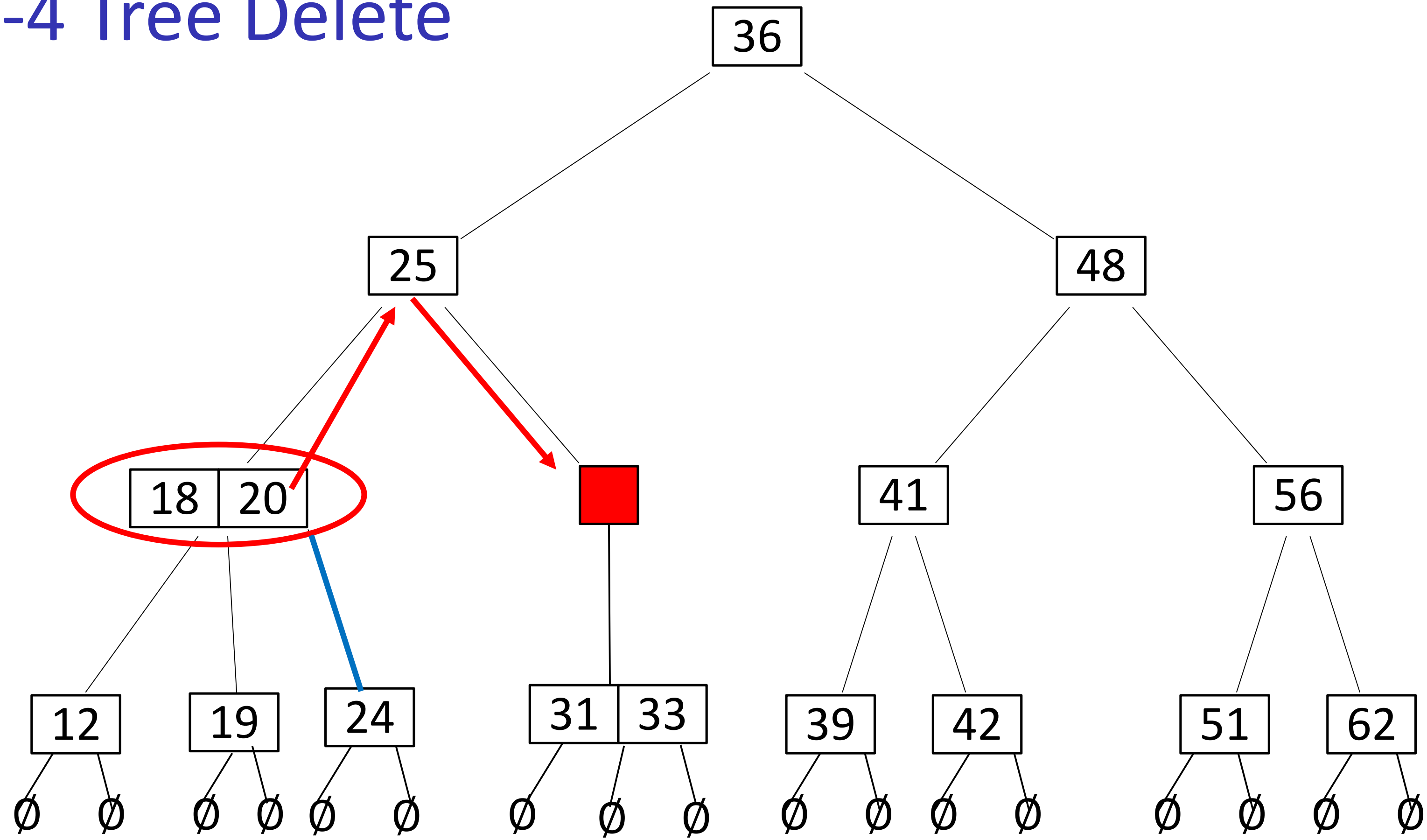
- Example: *delete*(28)
  - first search(28)
  - delete key 28 with one empty subtree
  - merge with the only immediate sibling, who is not rich

2-4 Tree Delete



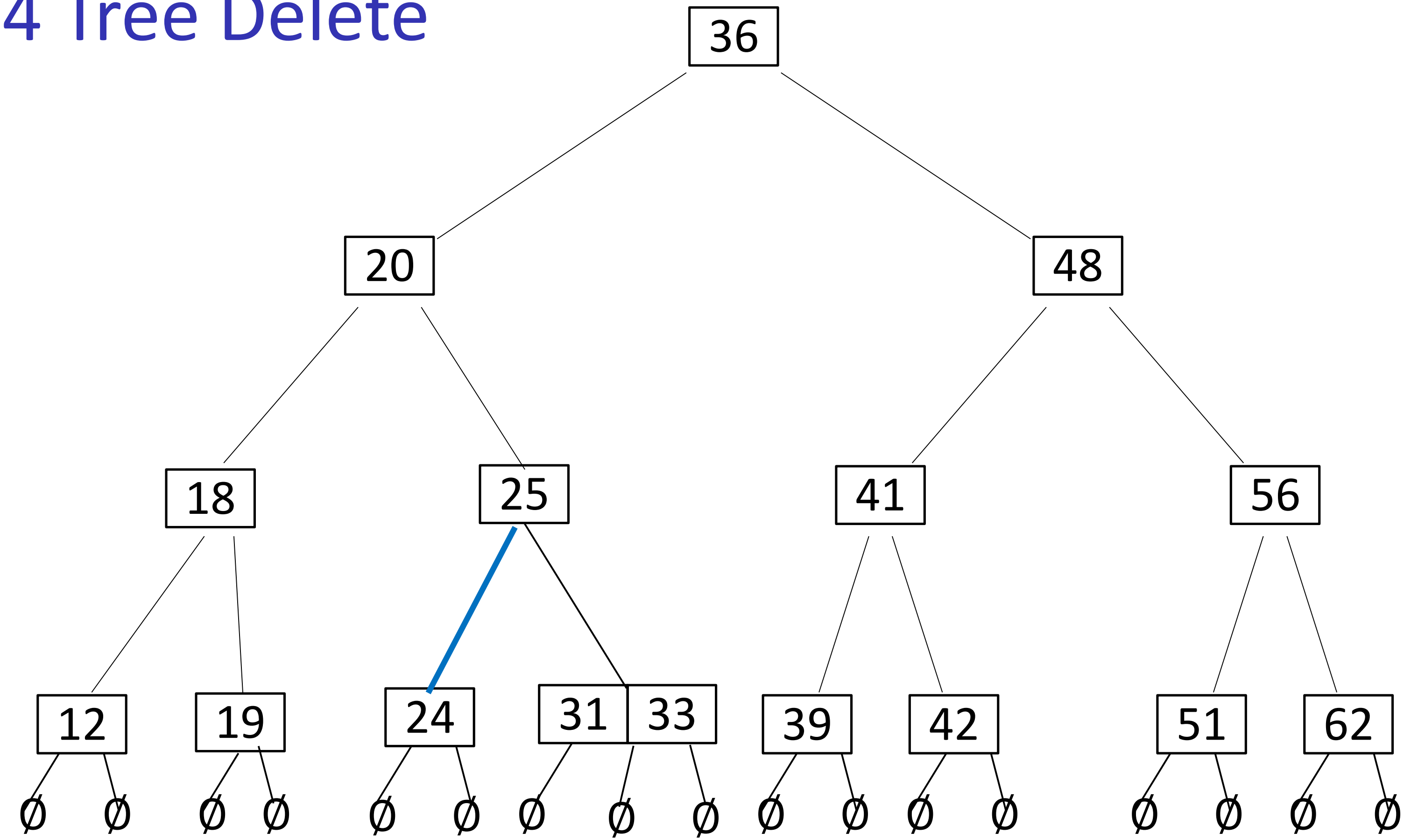
- Example: *delete*(28)
  - first search(28)
  - delete key 28 with one empty subtree
  - merge with the only immediate sibling, who is not rich

2-4 Tree Delete



- Example: *delete*(28)
  - transfer from a rich immediate sibling

2-4 Tree Delete



- Example: *delete*(28)
  - transfer from a rich immediate sibling
    - together with a subtree

2-4 Tree Delete Summary

- If key not at a leaf node, swap with inorder successor (guaranteed at leaf node)
- Delete key and one empty subtree from the leaf node involved in swap
- If underflow
  - If there is an immediate sibling with more than one key, transfer
    - no further underflows caused
      - do not forget to transfer a subtree as well
    - convention: if two siblings have more than one key, transfer with the right sibling
  - If all immediate siblings have only one key, merge
    - there must be at least one sibling, unless root
      - if root, delete
    - convention: if two immediate siblings with one key, merge with the right one
    - merge may cause underflow at the parent node, continue to the parent and fix it, if necessary

Deletion from a 2-4 Tree

```
24Tree::delete(k)
    v ← 24Tree::search(k)  //node containing k
    if v is not a leaf
            swap k with its inorder successor k′
            swap v with leaf that contained k′
    delete k  and one empty subtree in key-subtree-list of v
    while v has 0 keys // underflow
        if v is the root, delete v and break
        if v has immediate sibling u with 2 or more KVPs  // transfer, then done!
            transfer the key of u that is nearest to v to p
            transfer the key of p between u and v to v
            transfer the subtree of u that is nearest to  v to v
            break
        else // merge and repeat
            u ← immediate sibling of v
            transfer the key of p between u and v to u
            transfer the subtree of v to u
            delete node v
            v ← p
```

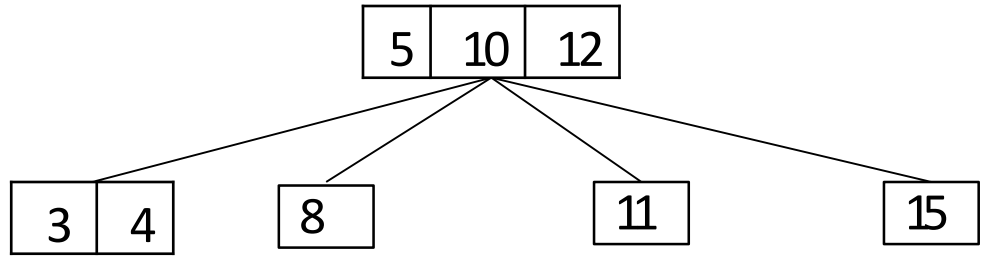
2-4 Tree Summary

- 2-4 tree has height $O(\log n)$
  - in internal memory, all operations have run-time $O(\log n)$
  - this is no better than AVL-trees in theory
  - but 2-4 trees are faster than AVL-trees in practice, especially when converted to binary search trees called red-black trees
- 2-4 tree has height $\Omega(\log n)$
  - n is the number of KVPs
  - for a tree of height h
    - $n \leq 3(4^0 + 4^1 \ldots + 4^h)$
    - $n \leq 4^{h+1} - 1$
    - $\log_4(n+1) - 1 \leq h$
  - thus h is $\Omega(\log n)$
- So 2-4 tree is not significantly better than AVL-tree wrt block transfers
- But can generalize the concept to decrease the height

Outline

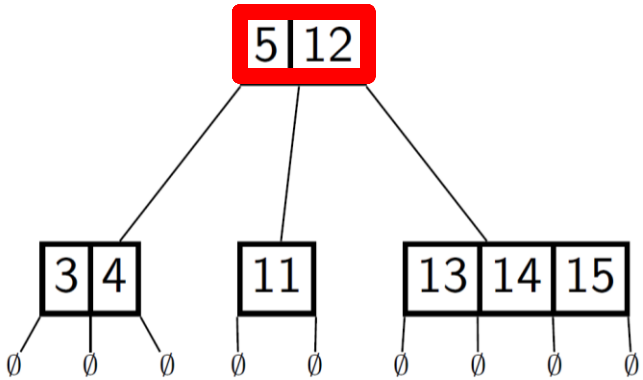
- External Memory
  - Motivation
  - Stream based algorithms
  - External sorting
  - External dictionaries
    - 2-4 Trees
    - red-black trees
    - (*a*, *b*)-Trees
    - B-Trees

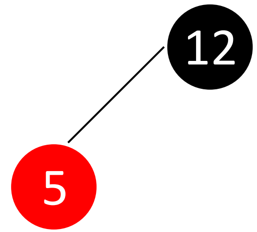
Problem with 2-4 trees



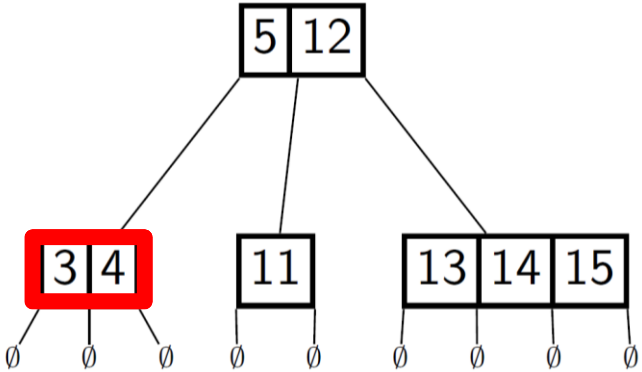
- Have 3 kinds of nodes
  - 1-node, 2-node, 3-node
  - need to store up to 7 items at each node
    - 3 keys and 4 subtree references
- How should we store keys and subtrees?
  - array of length 7
    - wastes space
  - linked list
    - overhead for list-nodes, also wastes space
  - theoretical bound not affected, but matters in practice
- Better idea
  - design a class of binary search trees that mirrors 2-4 tree

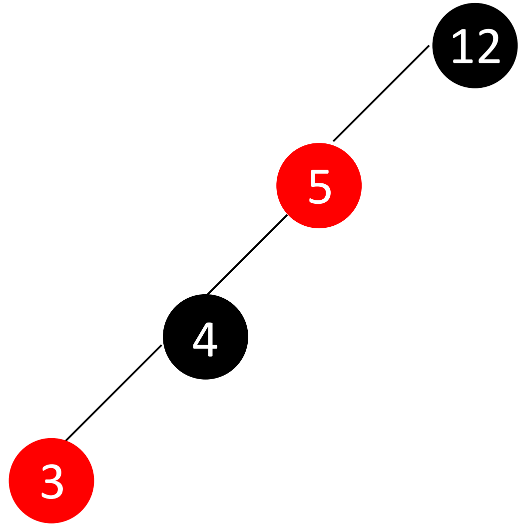
2-4 tree to red-black tree



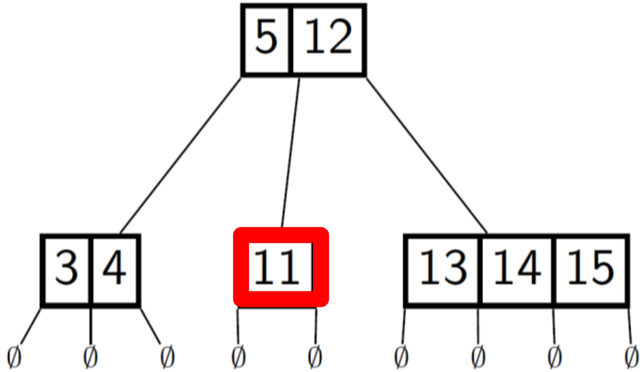


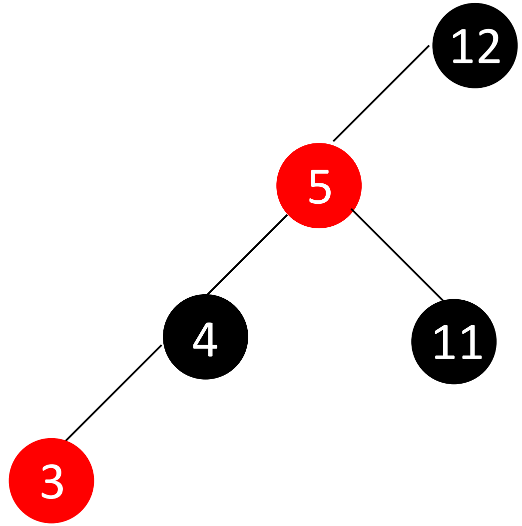
2-4 tree to red-black tree



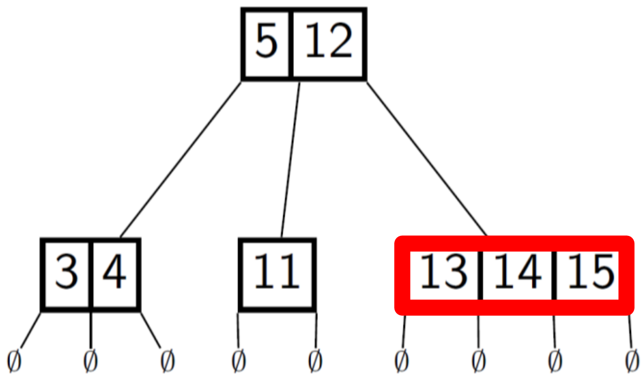


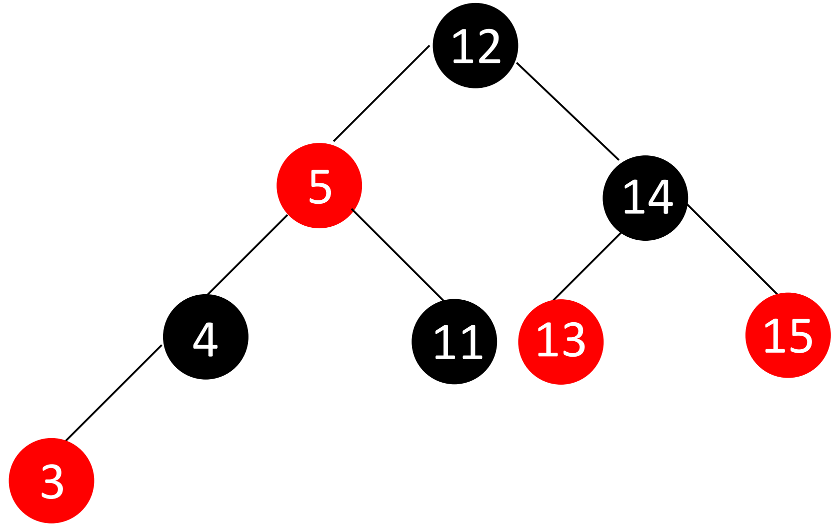
2-4 tree to red-black tree



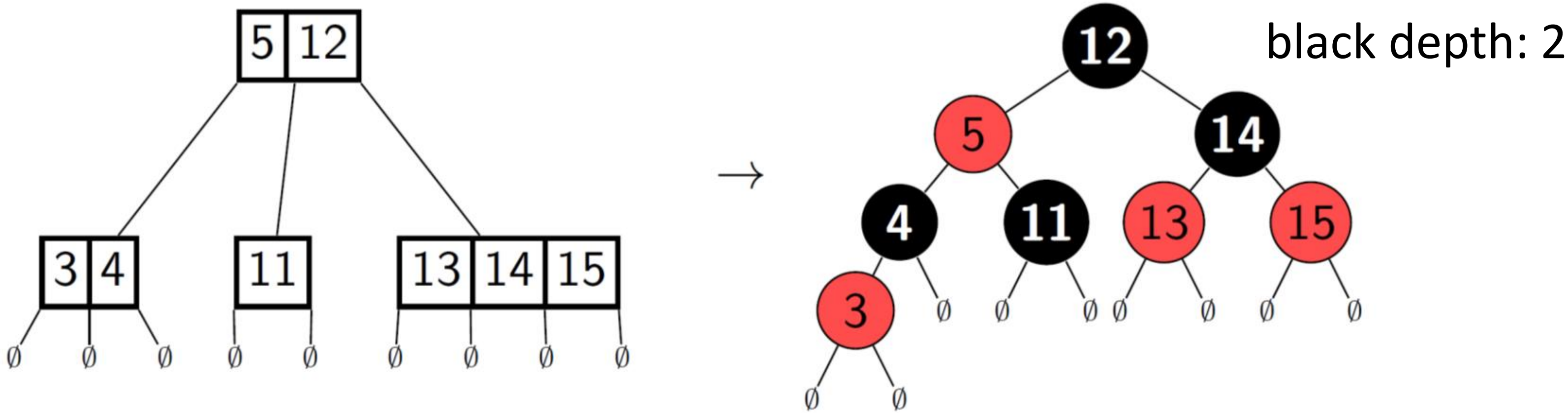


2-4 tree to red-black tree



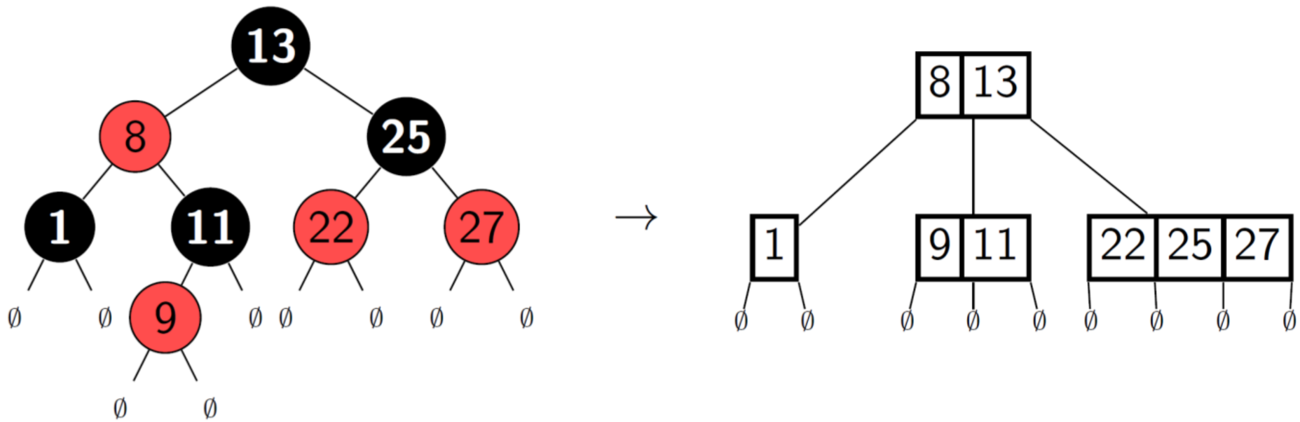


2-4 tree to red-black tree



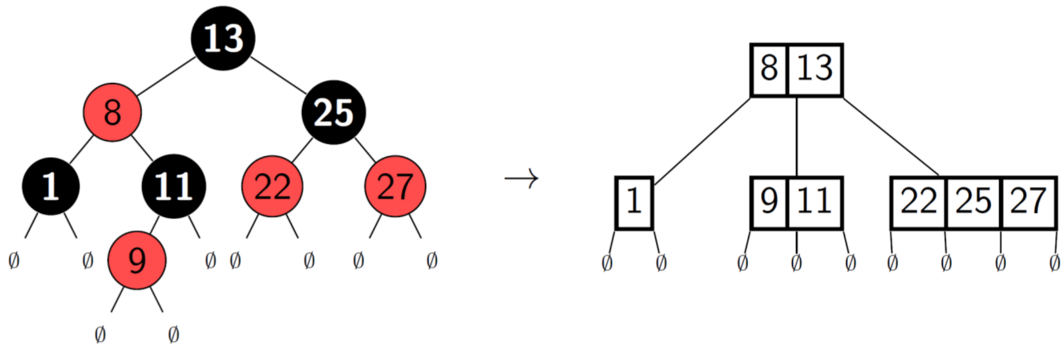
- Binary search tree that mirrors 2-4 tree
- d-node becomes a black node with $d - 1$ red children
  - assembled so that they form a BST of height at most 1
- Overhead: red/black 'color' is stored with just 1 extra bit per node
- Resulting properties
  - any red node has a black parent
  - any empty subtree of T has the same black-depth
    - number of black nodes on path form root to T

Red-Black tree to 2-4 tree



- Lemma: Any red-black tree can be converted to a 2-4 tree
- Proof:
    - black node with $0 \leq d \leq 2$ red children becomes a $(d+1)$ node
    - this covers all nodes
        - no red node has a red child
    - empty subtrees on the same level due to the same blackdepth

Red-Black tree to 2-4 tree



- Red-black trees have height $O(\log n)$
  - each level of 2-4 tree creates at most 2 levels in red-black tree
- Insert/delete can be done in $O(\log n)$ time
  - convert relevant part to 2-4 tree
  - do insert/delete as in 2-4 tree
  - convert relevant parts back to red-black tree
- Insert/delete can be done in $O(\log n)$ without conversion
  - no details
- Red/black trees are very popular balanced search trees (std::map)

Outline

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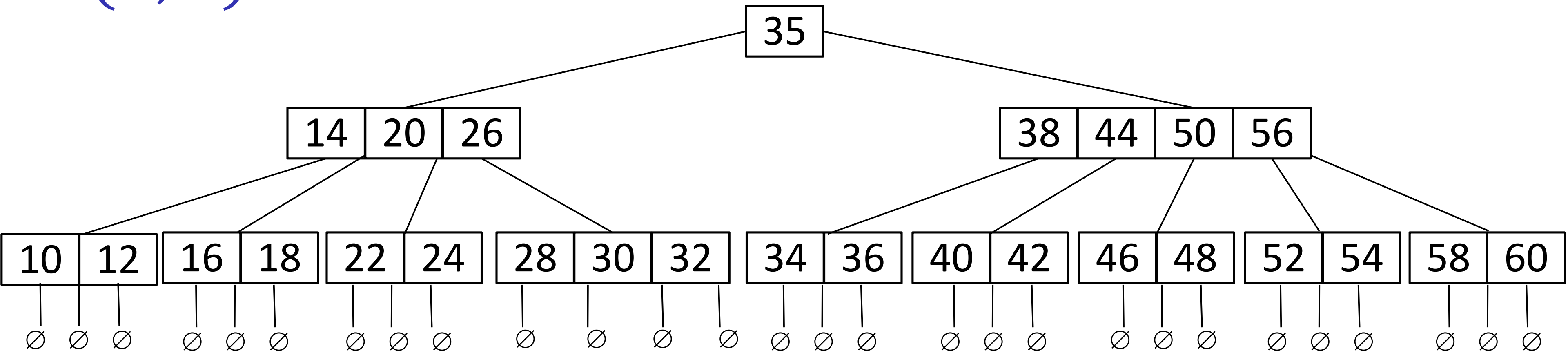
    - B-Trees

(a, b)-Trees

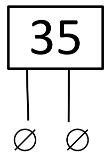
$(3, 5)$-tree, also a valid $(3, 6)$-tree



- 2-4 Tree is a specific type of (a, b)-tree
- (a, b)-tree satisfies
  - each node has at least a subtrees, unless it is the root
    - root must have at least 2 subtrees
  - each node has at most b subtrees
  - if node has d subtrees, then it stores $d - 1$ key-value pairs (KVPs)
  - all empty subtrees are at the same level
  - keys in the node are between keys in the corresponding subtrees
  - requirement: $b \geq 3$ and $2 \leq a \leq \left\lceil \frac{b}{2} \right\rceil$
    - lower bound on a is needed to bound height
    - upper bound on a is needed during operations

(a, b)-Trees: Root

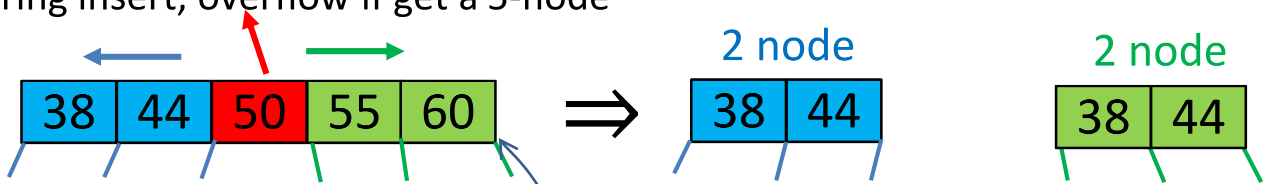
- Why special condition for the root?
- Needed for (a,b)-tree storing very few KVP
- (3,5) tree storing only 1 KVP



- Could not build it if forced the root to have at least 3 children
    - remember # keys at any node is one less than number of subtrees

(a, b)-Trees: Condition on a Explained

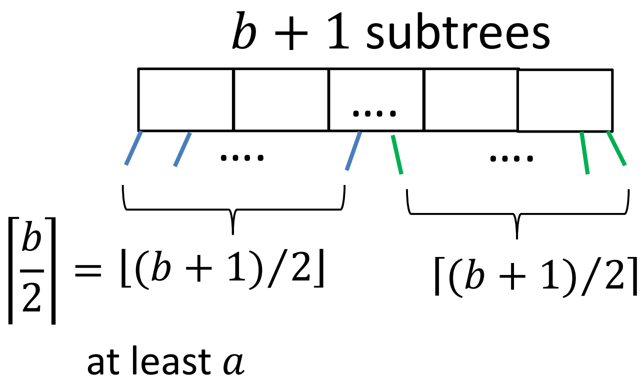
- Because $a \le \left\lceil \frac{b}{2} \right\rceil$ *search*, *insert*, *delete* work just like for 2-4 trees
  - straightforward redefinition of underflow and overflow
- For example, for $(3,5)$-tree
  - at least 3 children, at most 5
    - allowed: 2-node, 3-node, 4-node
  - during insert, overflow if get a 5-node



  - 2-node is smallest allowed node
- If $a > \left\lceil \frac{b}{2} \right\rceil$, no valid split exists for overflowed node
  - this is similar to requiring you split a pie in 2 parts, and each part is bigger than half!
  - for example if allow $(4,5)$-tree
    - allowed: 3-node, 4-node
    - overflow when get 5-node
    - equal (best possible) split of 5-node results in two 2-node
      - 2-node is not allowed for (4,5)-tree

(a, b)-Trees: Condition on a Explained

- Require $a \le \left\lceil \frac{b}{2} \right\rceil$
- Overflow means node has $b + 1$ subtrees

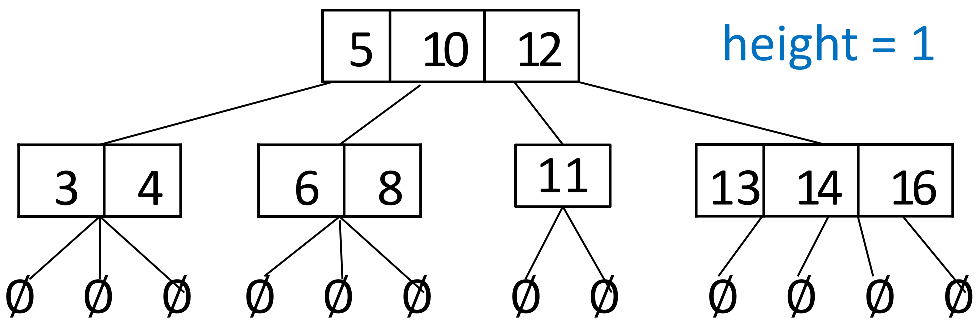


(a, b)-Trees Delete

- For example, for $(3,5)$-tree
  - at least 3 children, at most 5
    - each node is at least a 2-node, at most a 4-node
  - during delete, underflow if get a 1-node
  - if we have an immediate sibling which is rich (3 or 4-node), do transfer
  - otherwise, do merge
    - guaranteed to have at least one sibling which is a 2-node

Height of (a, b)-tree

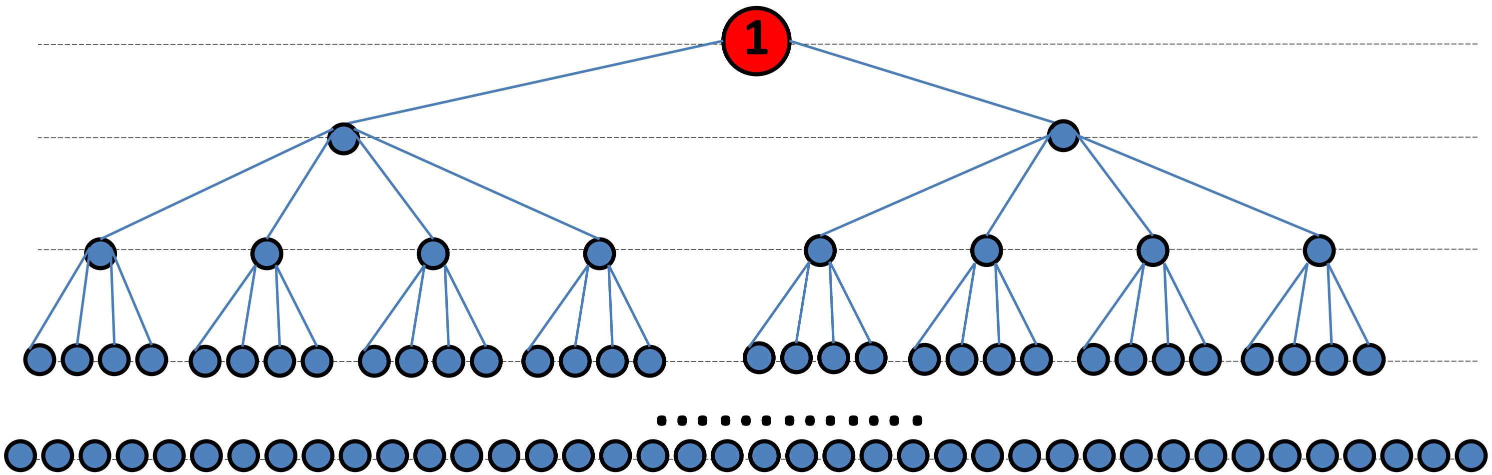
- Height = number of levels **not** counting empty subtrees



Height of (a, b)-tree

- Consider (a,b)-tree with the *smallest number* of KVP and of height h
  - red node (the root) has 1 KVP, blue nodes have $(a-1)$ KVP

level	# of nodes
0	1
1	$2a^0$
2	$2a^1$
3	$2a^2$
h	$2a^{h-1}$



$$\text{\# of KVPs} = \mathbf{1} + \sum_{i=0}^{h-1} 2a^i(a-1) = \mathbf{1} + 2(a-1)\sum_{i=0}^{h-1} a^i = 2a^h - 1$$

$$\sum_{i=0}^{h-1} a^i = \frac{a^h - 1}{a - 1}$$

- Let n the number of KVP in *any* (a, b)-tree of height h

$$n \geq 2a^h - 1 \text{, therefore, } \log_a \frac{n+1}{2} \geq h$$

- Height of tree with n KVPs is $O(\log_a n) = O(\log n / \log a)$

(a, b)-Tree Analysis in Internal/External Memory

- Internal memory
  - search, insert, delete each require visiting $\Theta(height)$ nodes
  - height is $O(\log n / \log a)$
  - recall that $a \leq \left\lceil \frac{b}{2} \right\rceil$ is required for insert and delete to work correctly
  - therefore, chose $a = \left\lceil \frac{b}{2} \right\rceil$ to minimize the height
  - store from a to b items at a node: work at a node can be done in $O(\log b)$ time
  - total cost

$$O\left(\frac{\log n}{\log a} \cdot \log b\right) = O\left(\frac{\log n}{\log \left\lceil \frac{b}{2} \right\rceil} \cdot \log b\right) = O\left(\frac{\log b}{\log b - 1} \cdot \log n\right) = O(\log n)$$

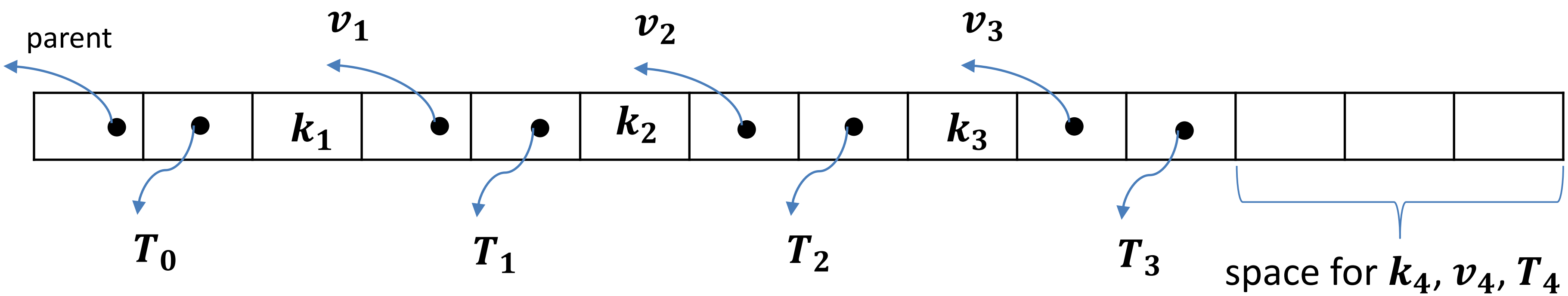
  - this is not better than AVL-trees in internal memory
- External memory
  - we count just block transfers
  - running time is $O(\log n / \log a)$, assuming each node fits into one block
  - makes sense to make a as large as possible so that a node still fits into one block

Outline

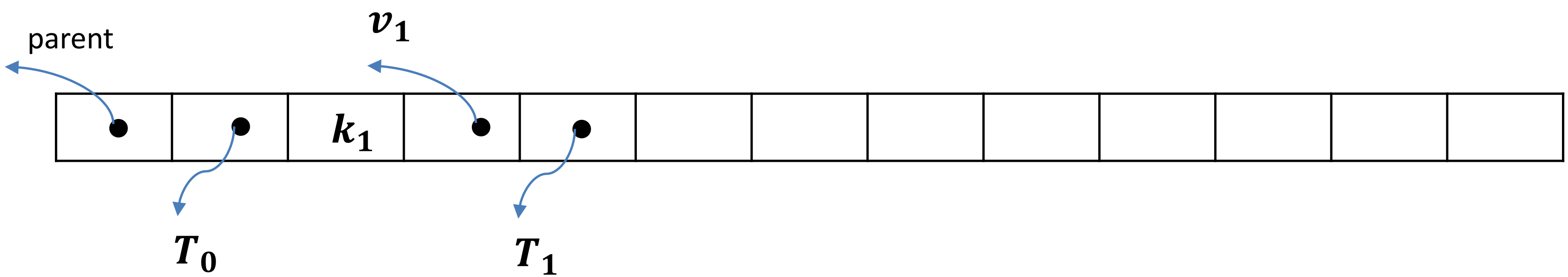
- External Memory
  - Motivation
  - Stream based algorithms
  - External sorting
  - External dictionaries
    - 2-4 Trees
    - red-black trees
    - (*a*, *b*)-Trees
    - B-Trees

B-trees: Motivation

- B-tree is a type of (a, b)-tree tailored to the external memory model
- Each block in external memory stores one tree node



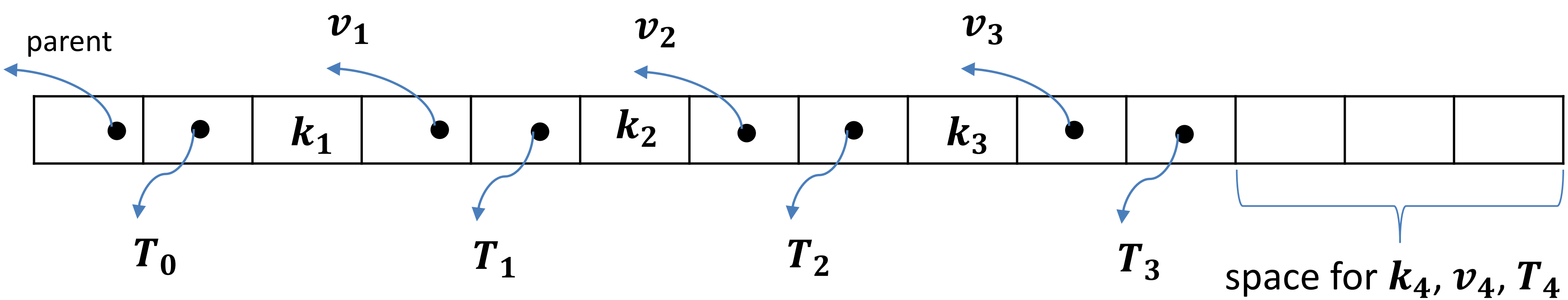
- If allow small a, would waste most block space



- Height is $O(\log n / \log a)$, so small a leads to large height and wasted space
- Choose b so that the largest node (b subtrees) fits into one block
  - store $b-1$ keys directly (not through reference)
  - $b-1$ value references, b subtree references, reference to parent

B-trees: Definition

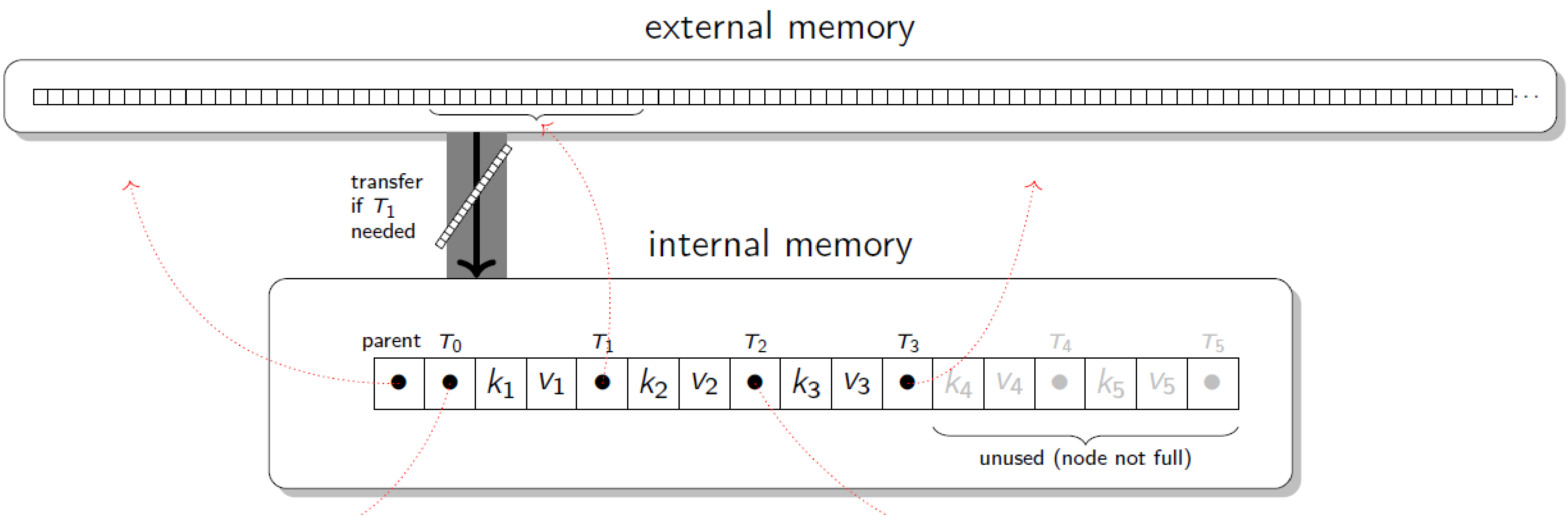
- For external memory use (a, b)-tree s.t.
  - largest possible node (i.e. b subtrees) still fits into a block
  - and a is as large as possible, recall that largest allowed $a = \lceil b/2 \rceil$
  - each block will be at least half full
- Thus use $(\lceil b/2 \rceil, b)$- tree for external memory
- This is defined as B-tree
- We usually specify B-tree by just giving b
  - b is called the order of B-tree
  - B-tree or order b is a $(\lceil b/2 \rceil, b)$-tree
- Example: node for B-tree of order 5



- Typically $b \in \Theta(B)$
  - $B = b * const$

B-trees in External Memory

- Close-up on one node in one block



- In this example, 12 references and 5 keys fit into one block, so B-tree can have order 6
- Values can be stored in the block directly if they do not need much space, otherwise store them by reference
  - storing values by reference is ok as we do not need values during tree search

B-tree Analysis in External Memory

- Search, insert, and delete each requires visiting $\Theta(height)$ nodes
  - $\Theta(height)$ block transfers
- Work within a node is done in internal memory, no block transfers
- The height is $\Theta(\log_b n)$ which is $\Theta(\log_B n)$
  - since $b \in \Theta(B)$
  - Proof (assuming $b \geq B/3$ and $B \geq 9$):

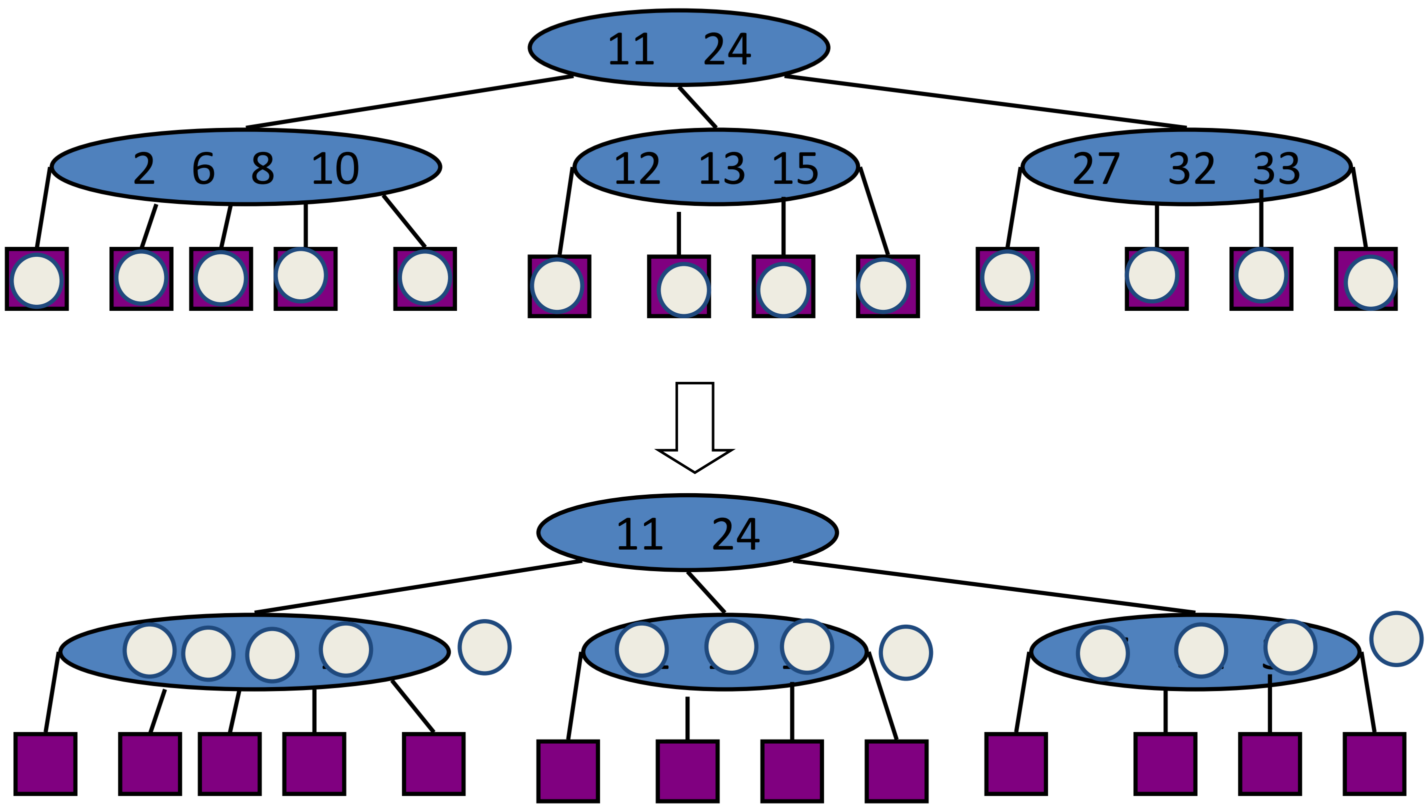
$$\log_b n = \frac{\log n}{\log b} \leq \frac{\log n}{\log B/3} \leq \frac{\log n}{\log \sqrt{B}} = 2 \log_B n$$

- So all operations require $\Theta(\log_B n)$ block transfers
  - can show that this is asymptotically optimal
- There are variants that are even better in practice
- B-trees are hugely important for storing databases (cs448)

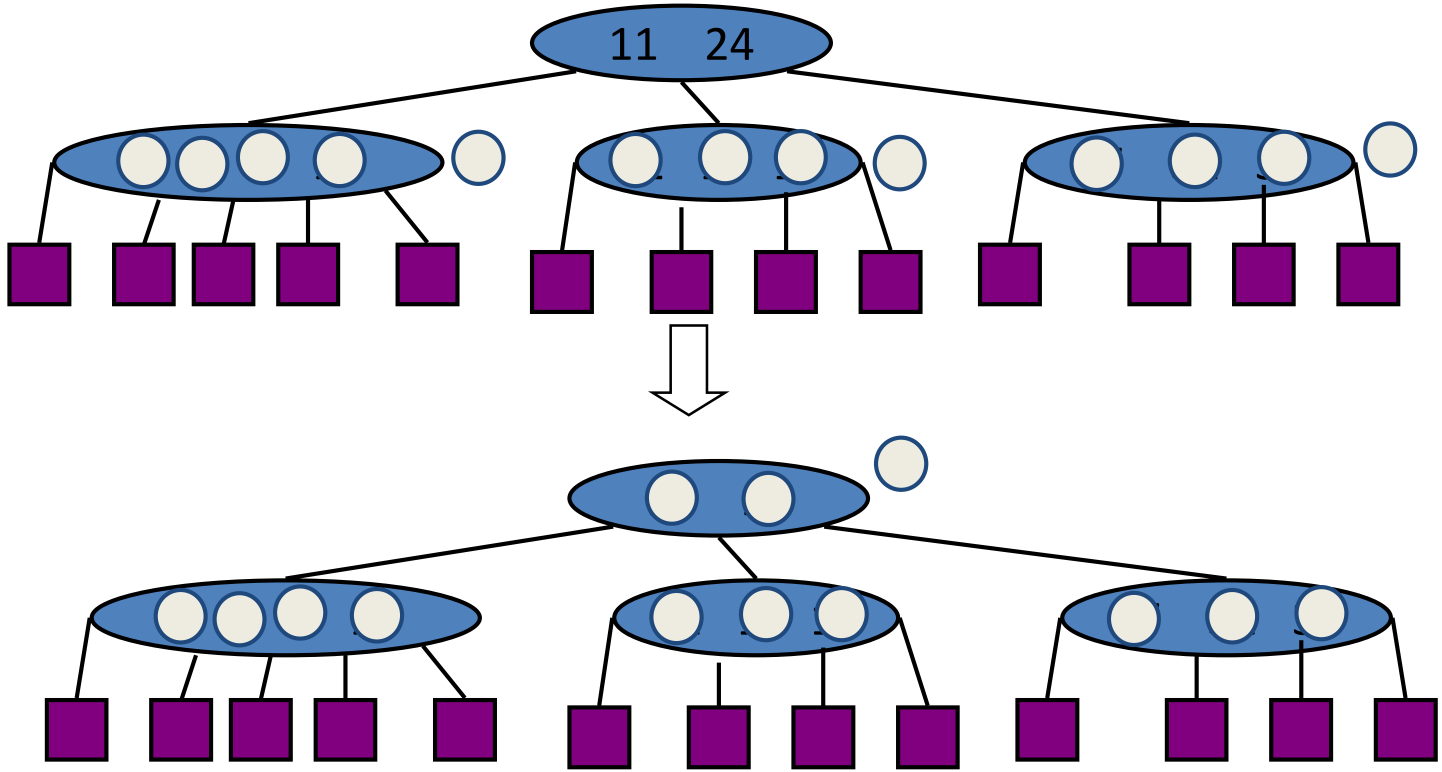
Useful Fact about (a, b)-trees

- number of of KVP = number of empty subtrees – 1 in any (a, b)-tree

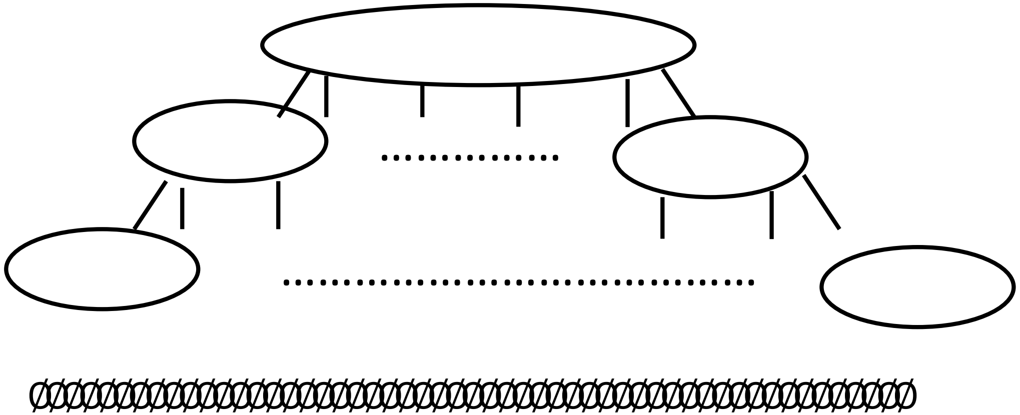
Proof: Put one stone on each empty subtree and pass the stones up the tree. Each node keeps 1 stone per KVP, and passes the rest to its parent. Since for each node, #KVP = # children – 1, each node will pass only 1 stone to its parent. This process stops at the root, and the root will pass 1 stone outside the tree. At the end, each KVP has 1 stone, and 1 stone is outside the tree.



Useful Fact about (a, b)-trees



Example of B-tree usage



1 node (root)

200 nodes

200^2 nodes

200^3 empty subtrees

- B-tree of order 200
    - B-tree of order 200 and height 2 can store up to $200^3 - 1$ KVPs
    - if we store root in internal memory, then only 2 block reads are needed to retrieve any item
    - compare: AVL tree of height at least 23 to store as many KVPs