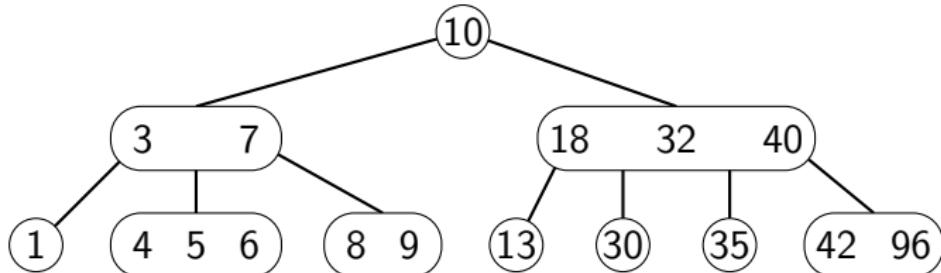


2-3-4 trees II: Deletion and alternative forms

COMS20017 (Algorithms and Data)

John Lapinskas, University of Bristol

Summary of a 2-3-4 tree with distinct values (so far)



Finding a value v : Let x be the root. If $v \in x$, return a pointer to x . Otherwise, if x is a leaf, return Not Found. Otherwise, let k be such that x is a k -node, let $x_1 \leq \dots \leq x_{k-1}$ be the values in x , let $x_0 = -\infty$, and let $x_k = \infty$; then $x_{i-1} < v < x_i$ for some i . Let c be the i 'th child of x . Then repeat the process from the start, taking $x = c$.

Inserting a value v : First attempt to find v as above, **splitting** any 4-nodes encountered (including the root). After reaching a leaf L , and splitting it if it is a 4-node, add v to L .

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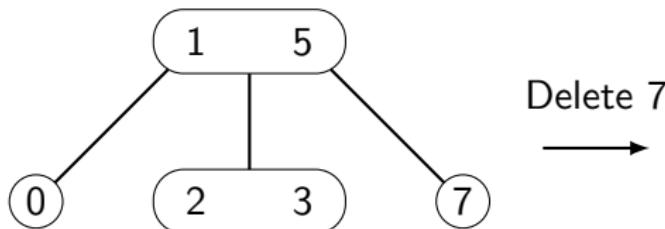
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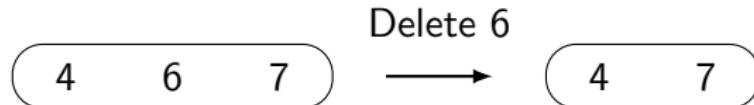
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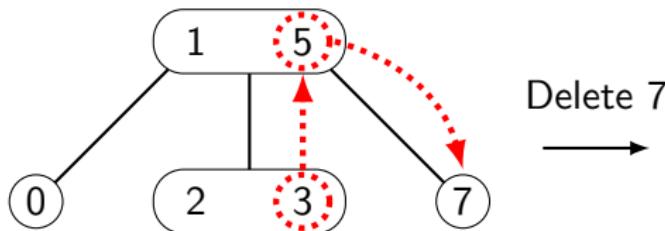
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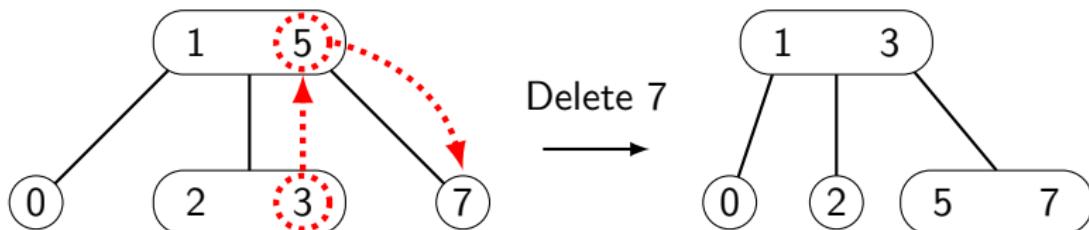
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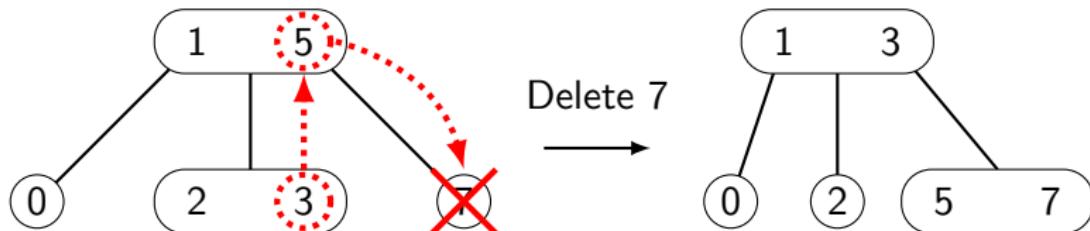
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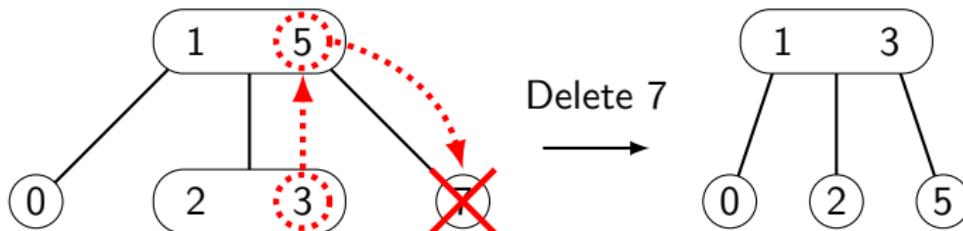
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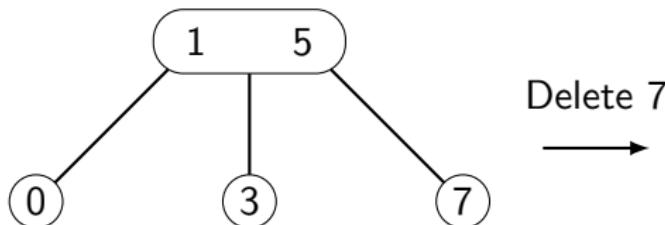
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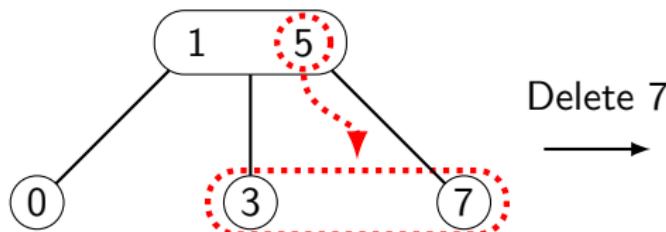
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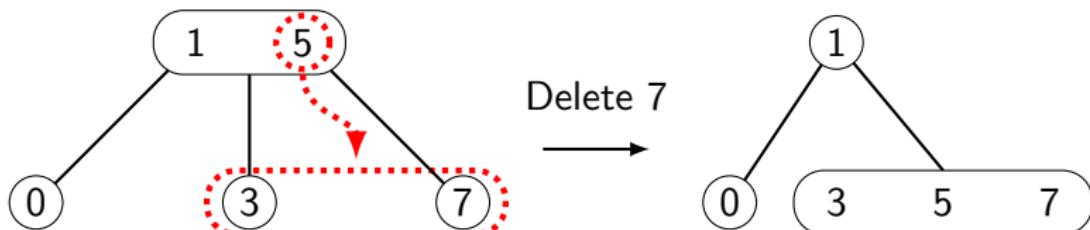
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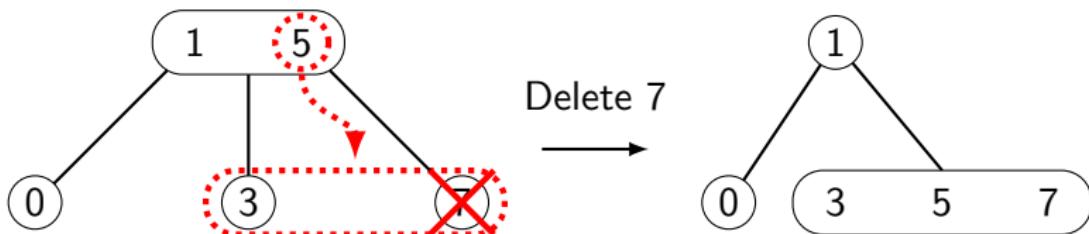
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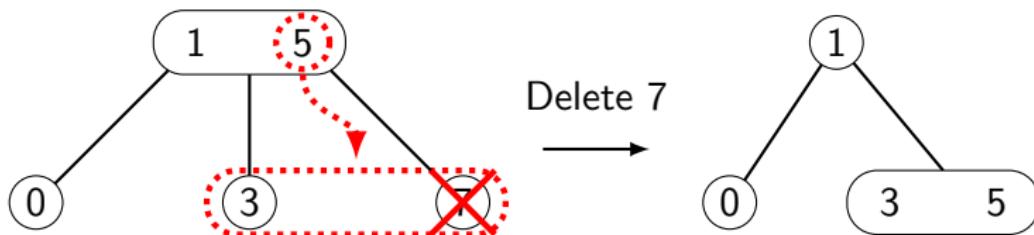
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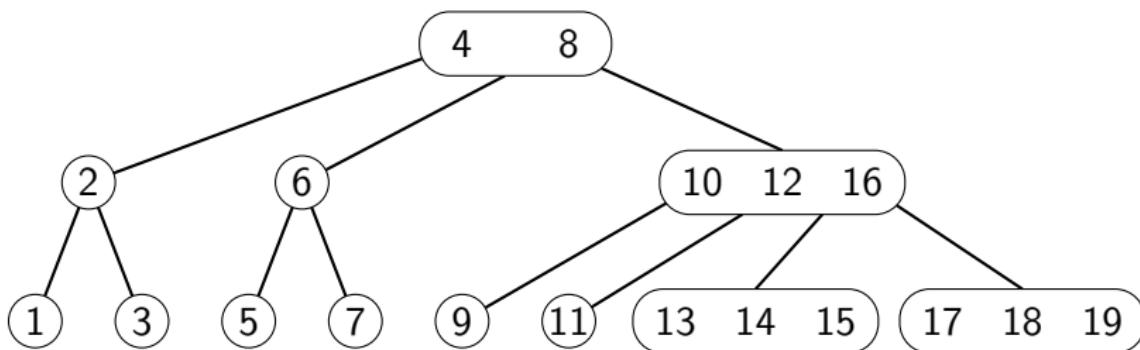
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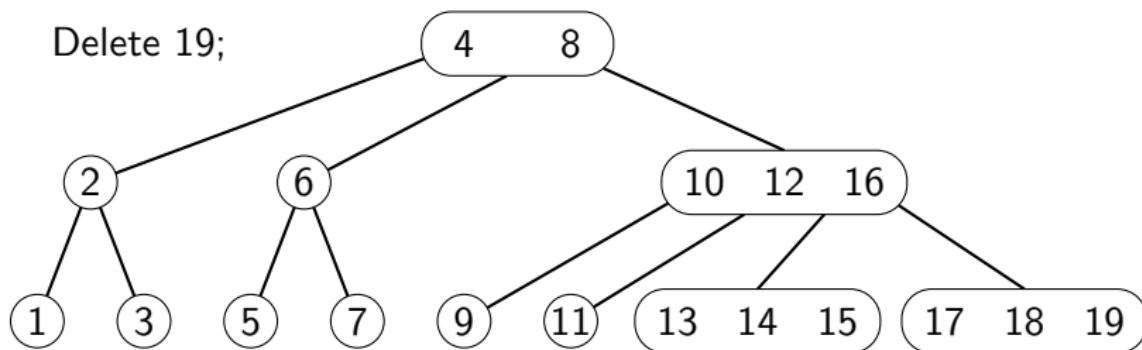
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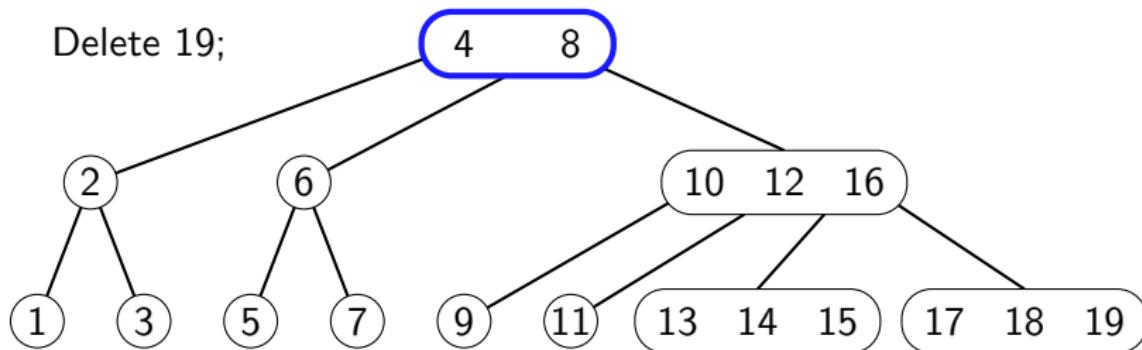
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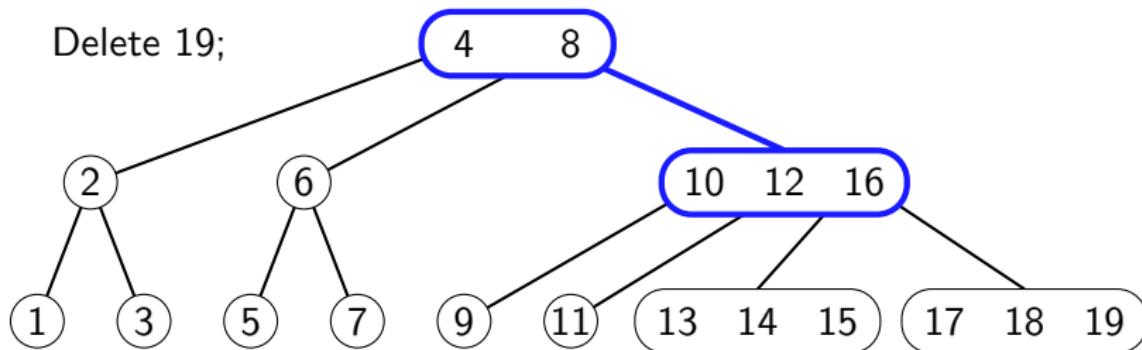
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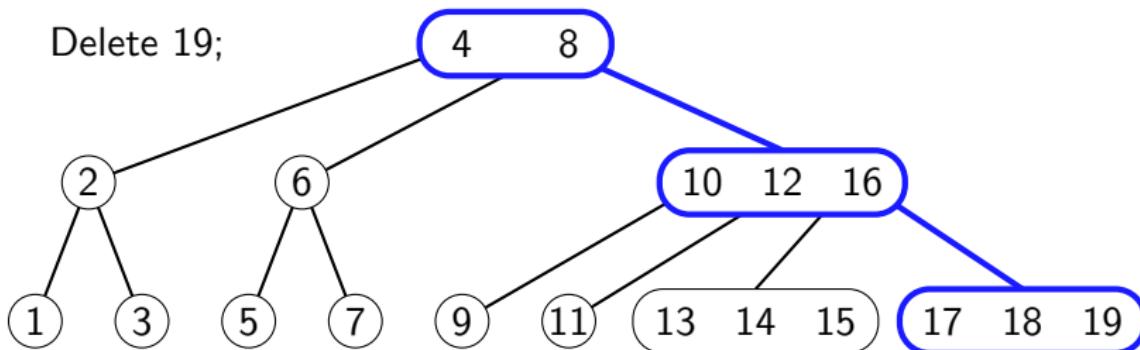
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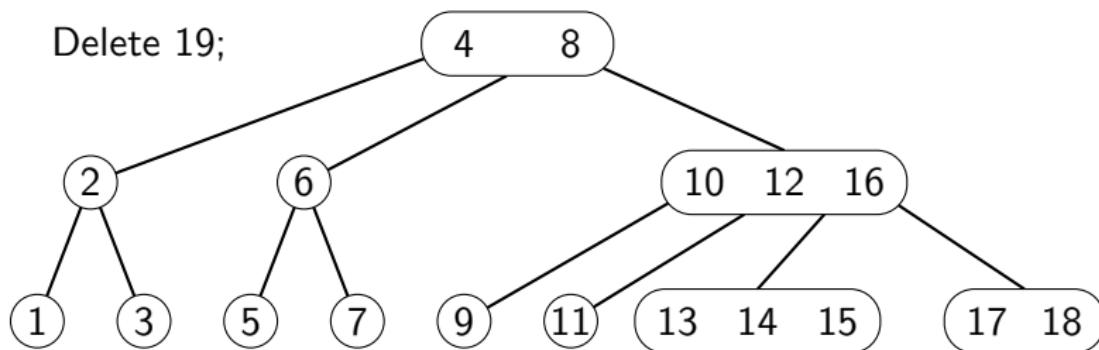
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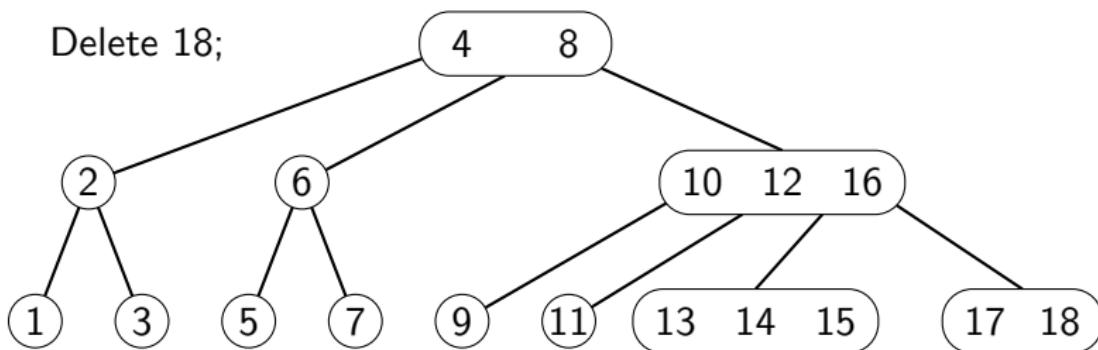
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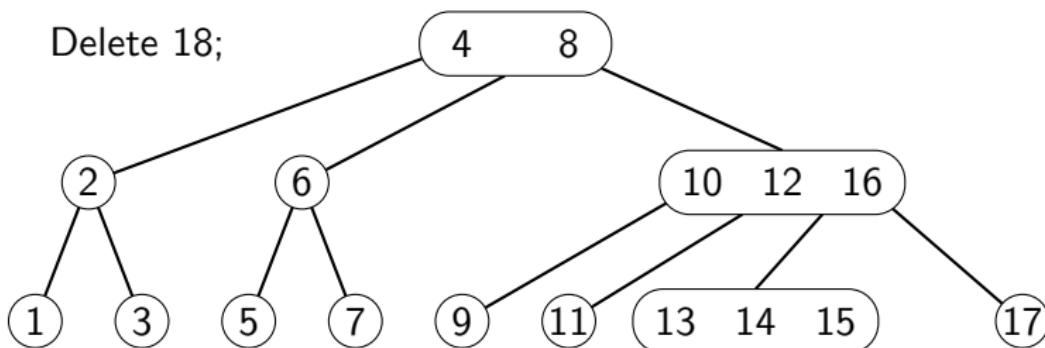
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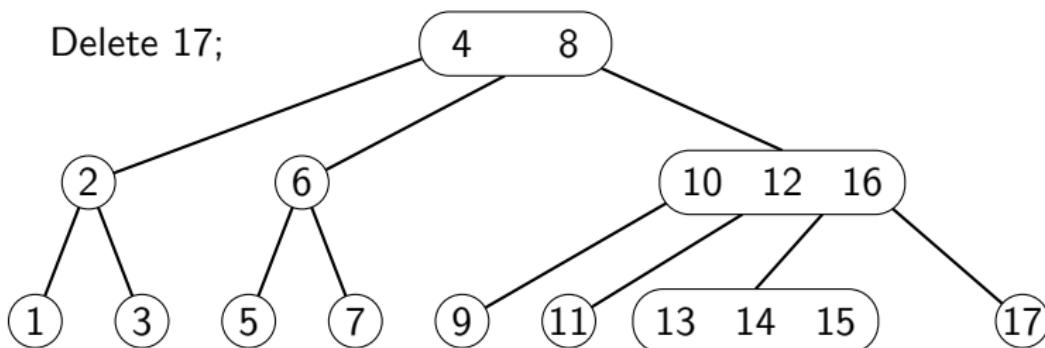
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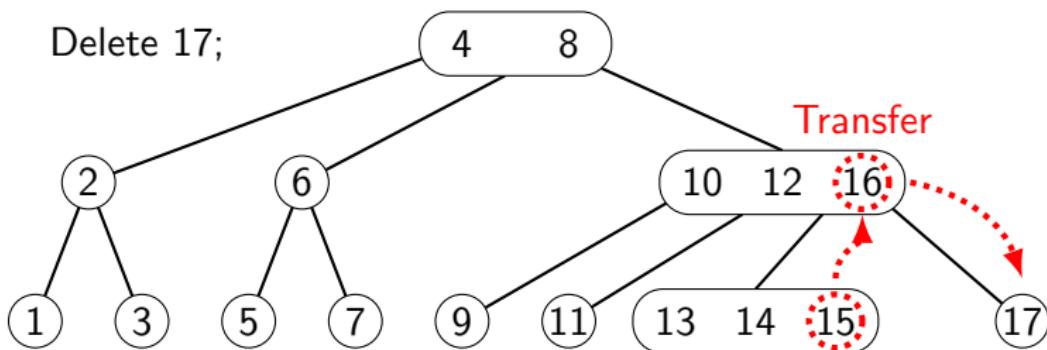
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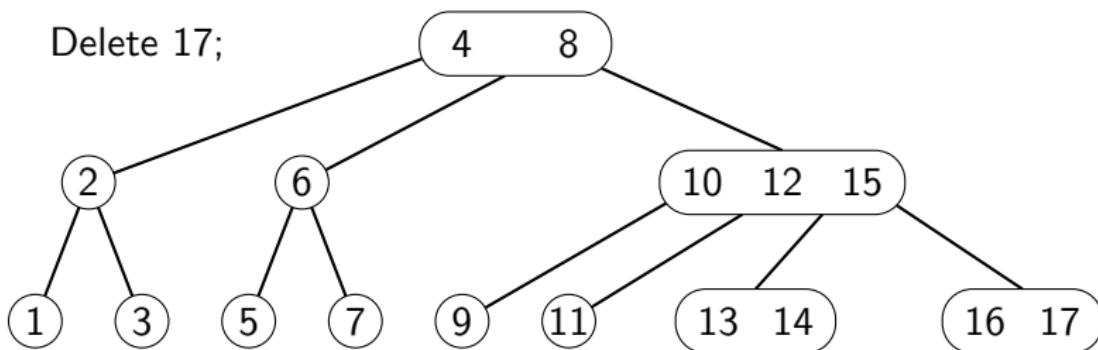
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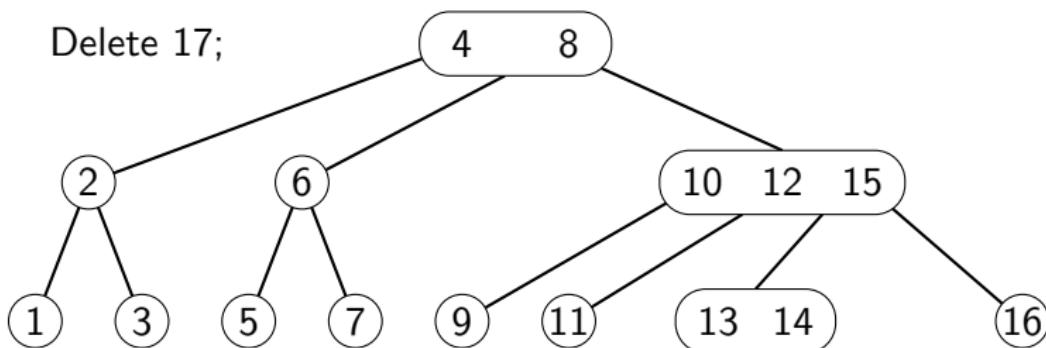
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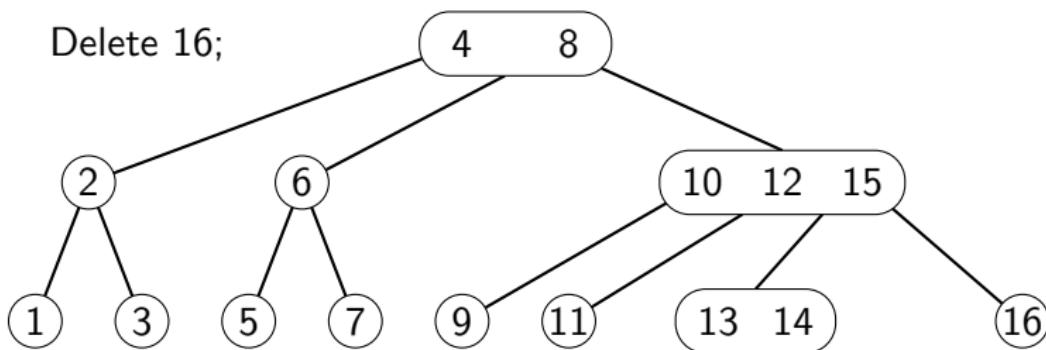
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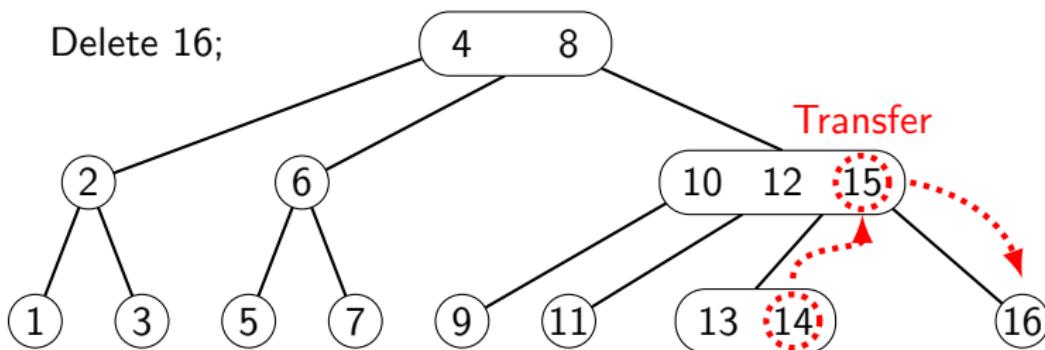
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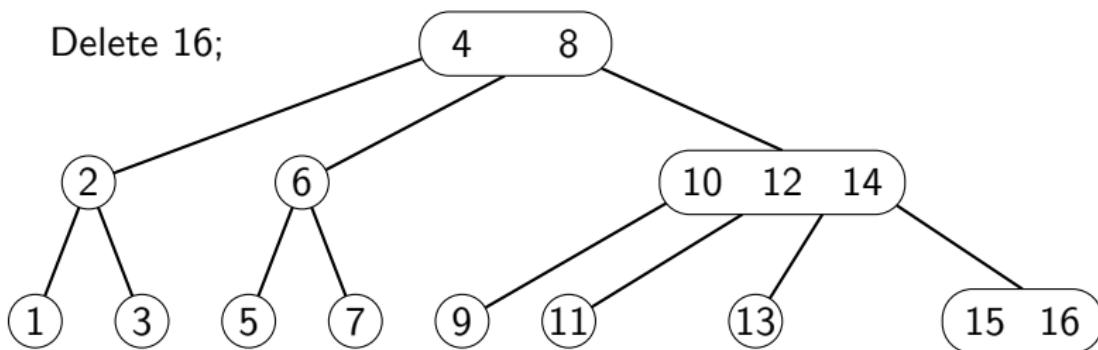
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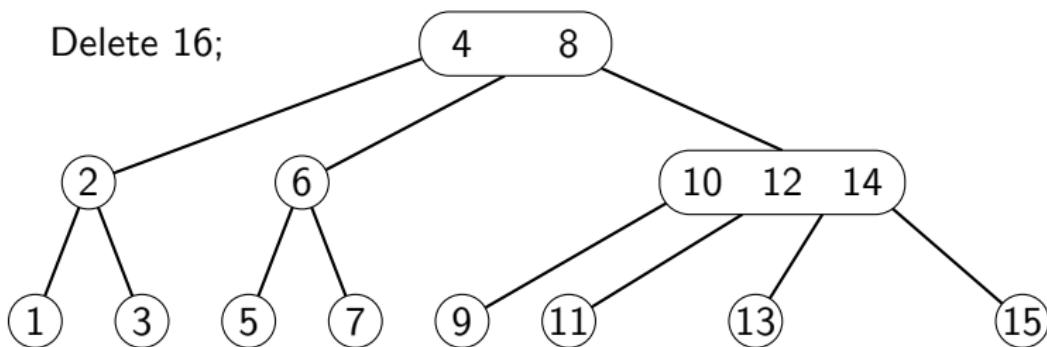
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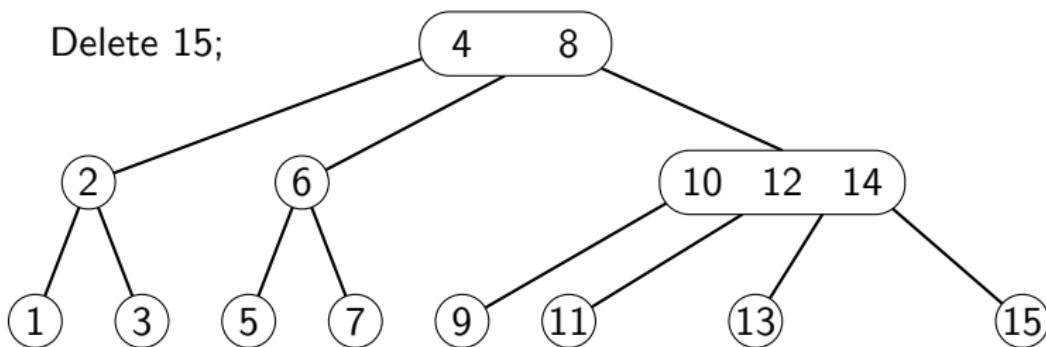
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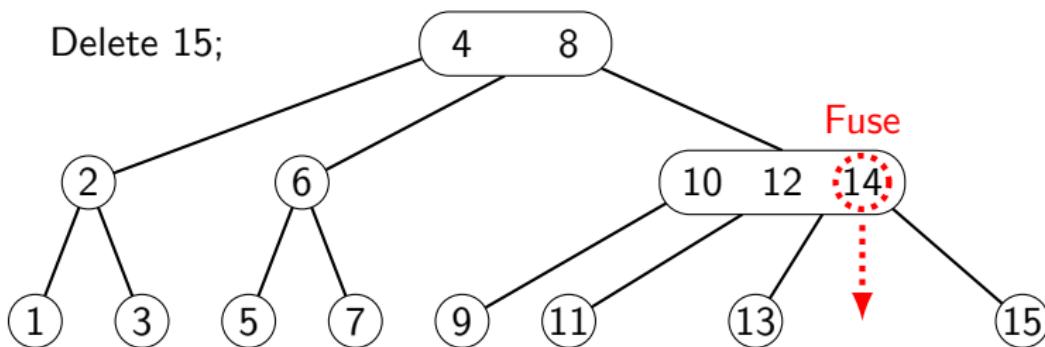
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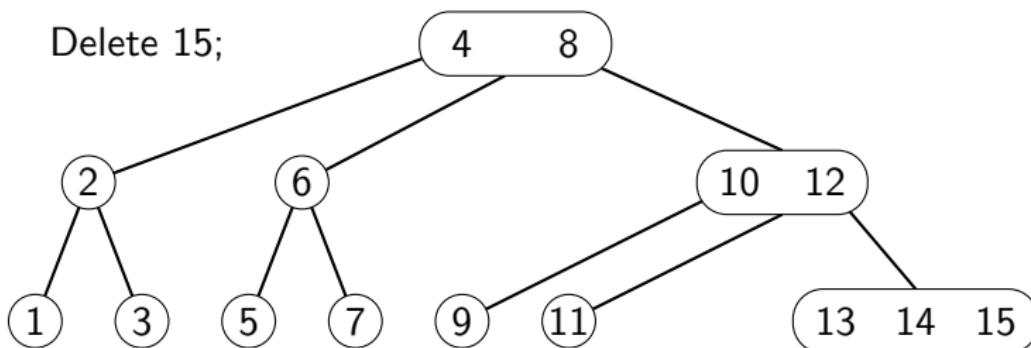
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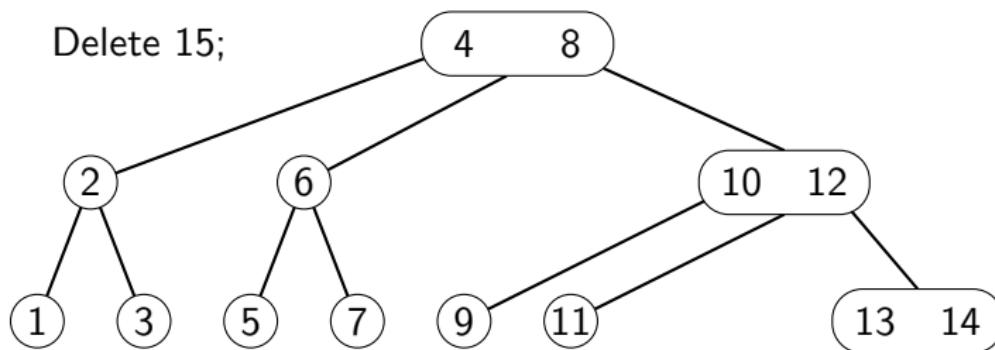
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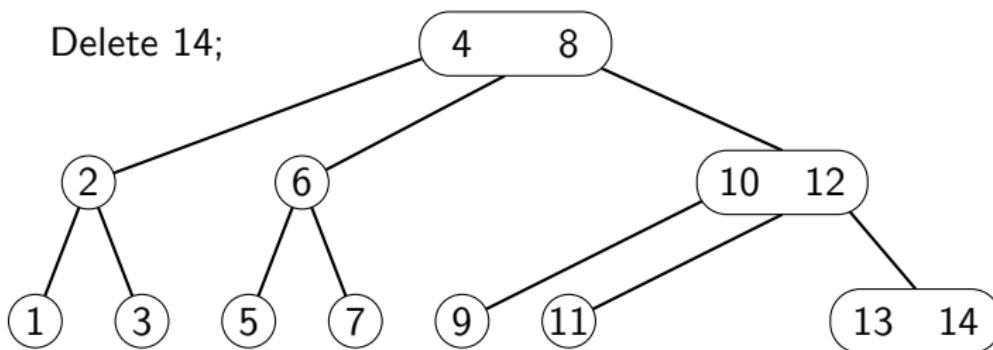
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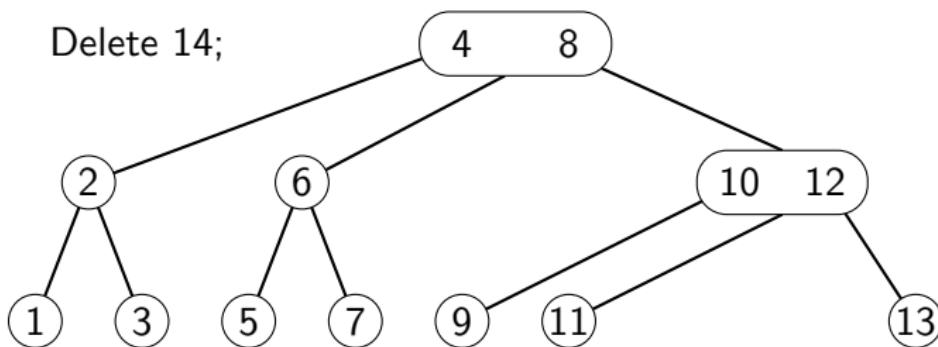
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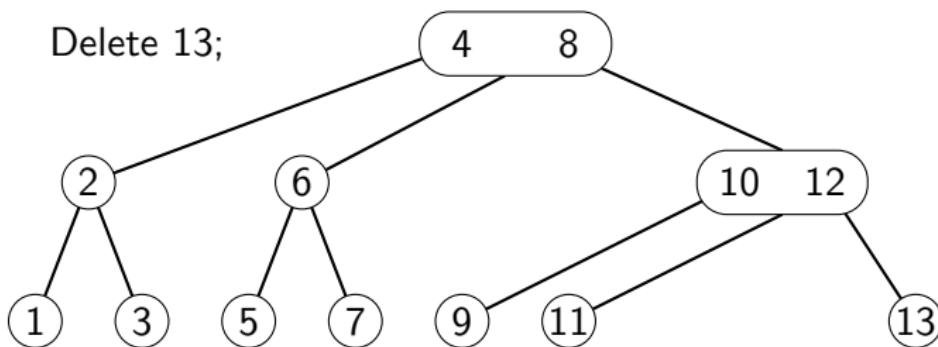
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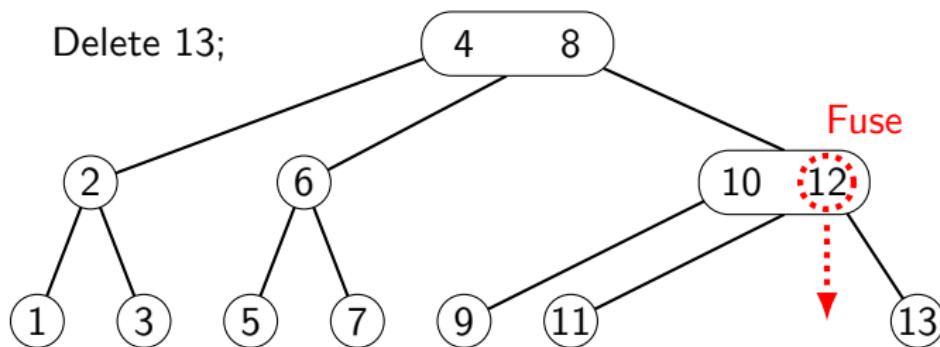
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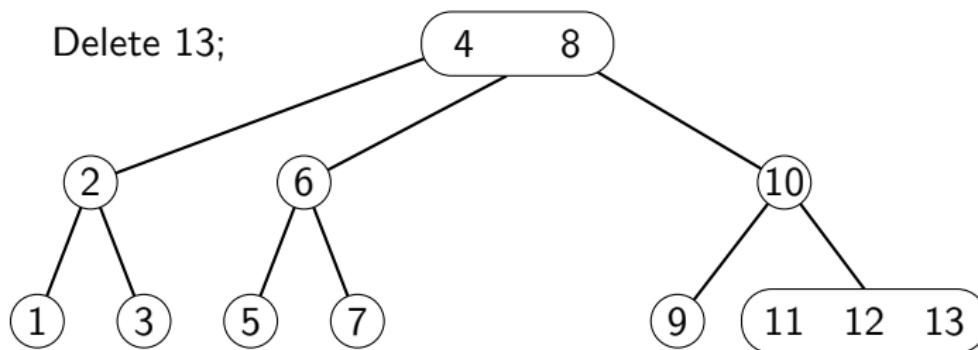
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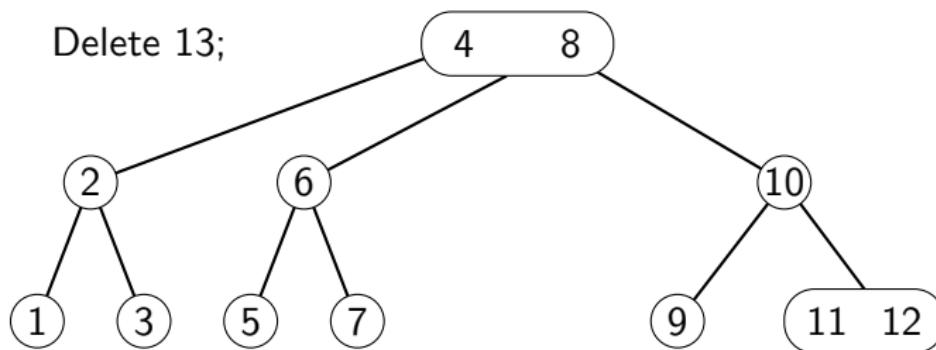
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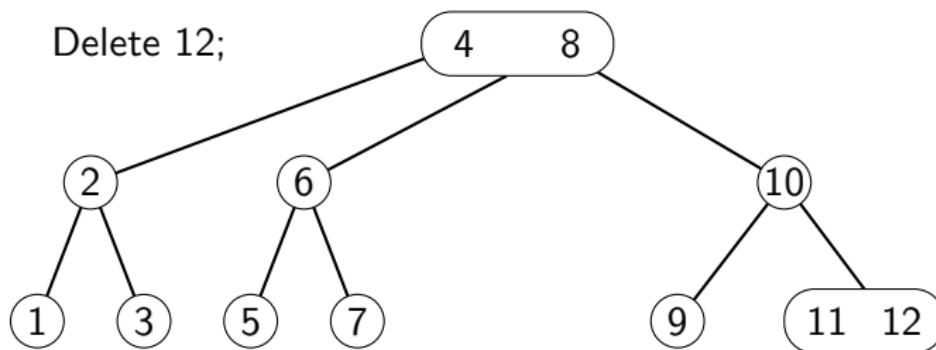
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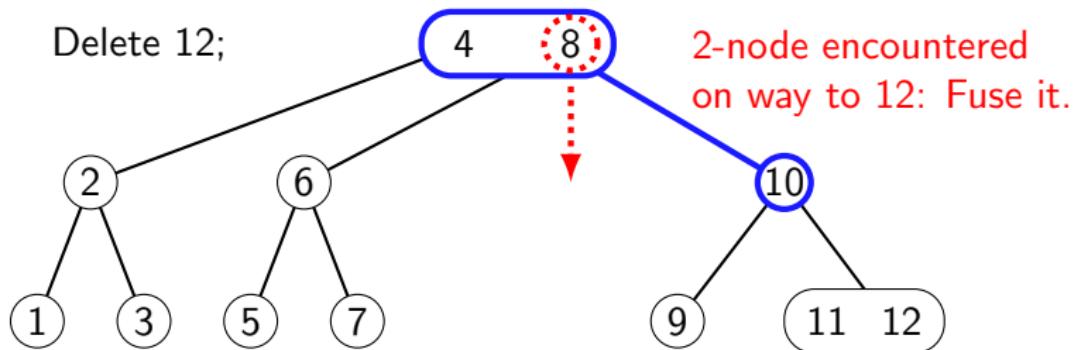
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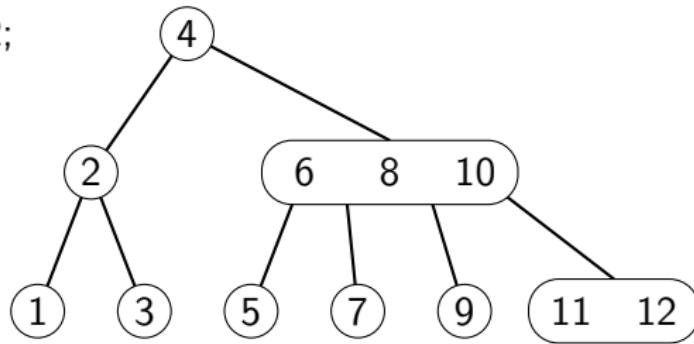
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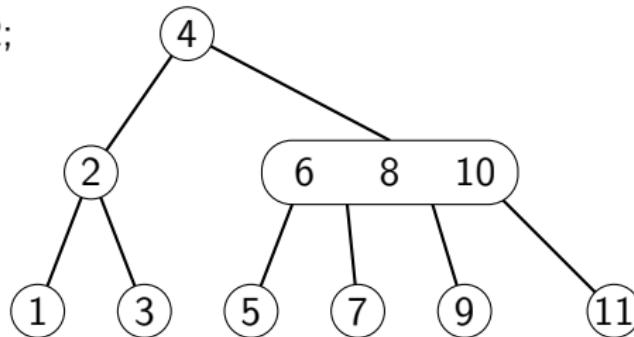
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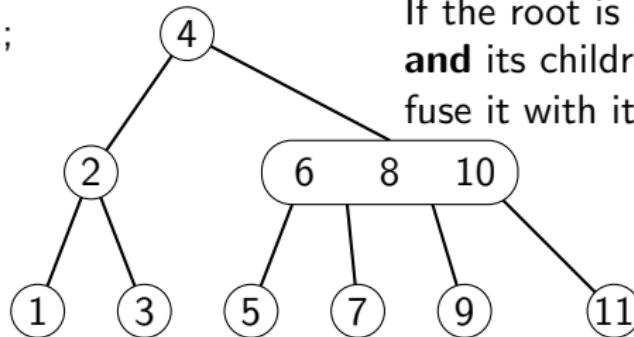
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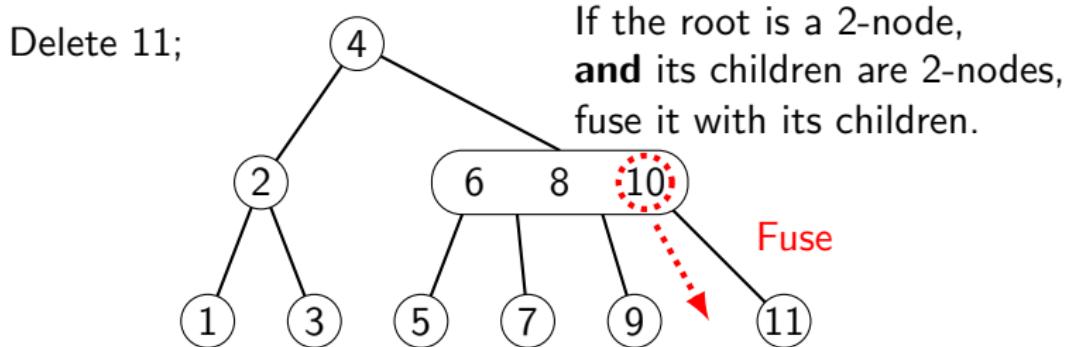
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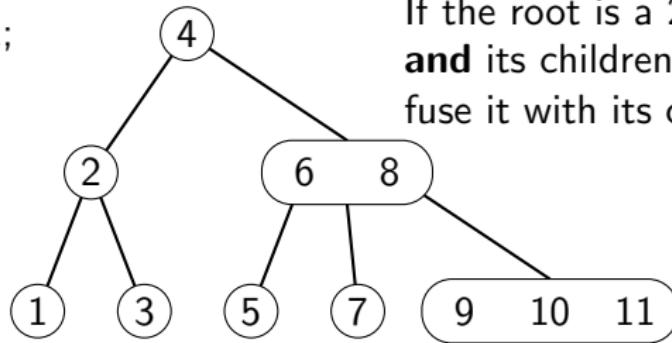
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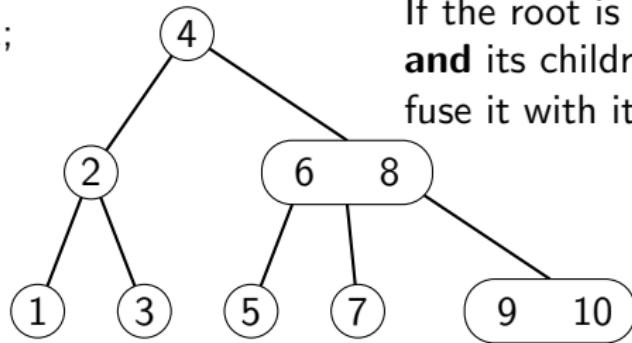
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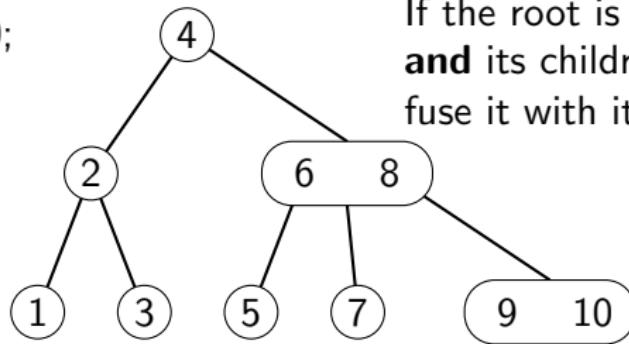
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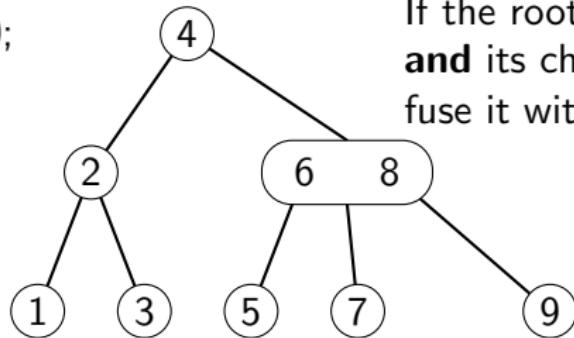
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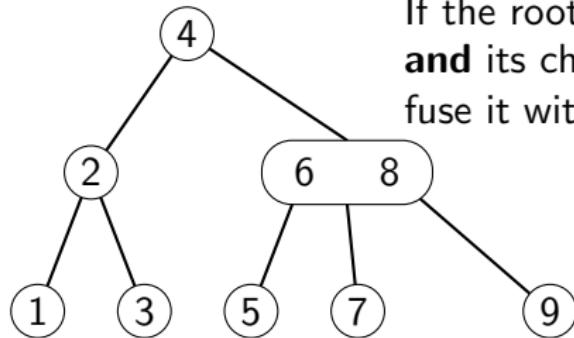
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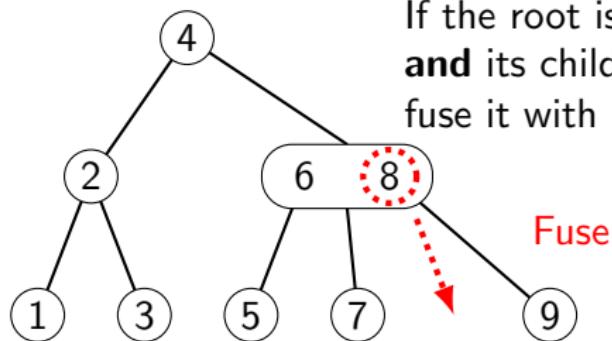
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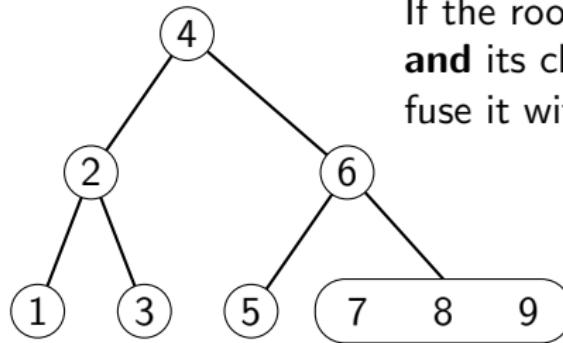
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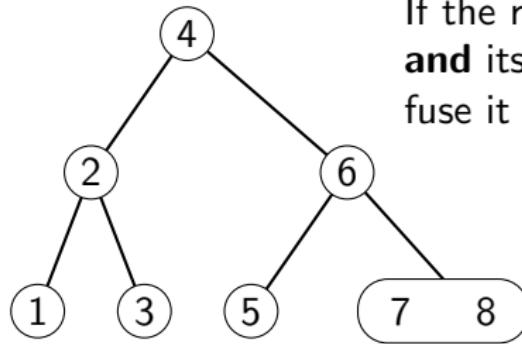
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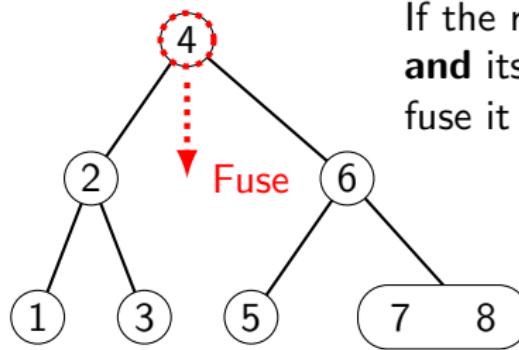
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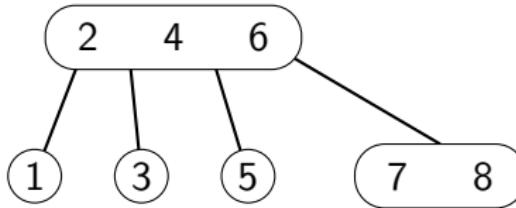
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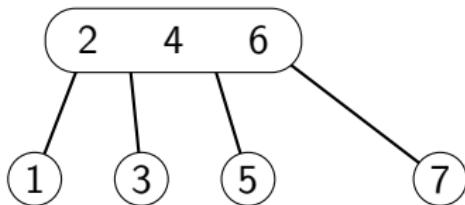
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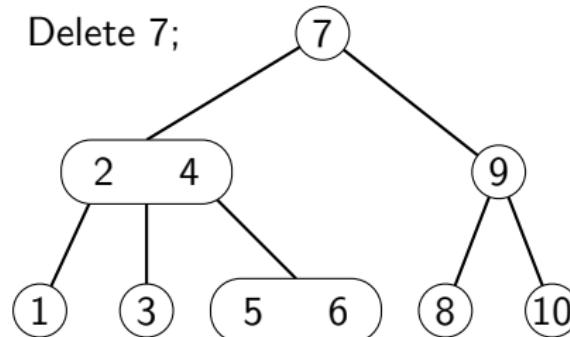
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So let's **reduce** the problem to deleting from a leaf!

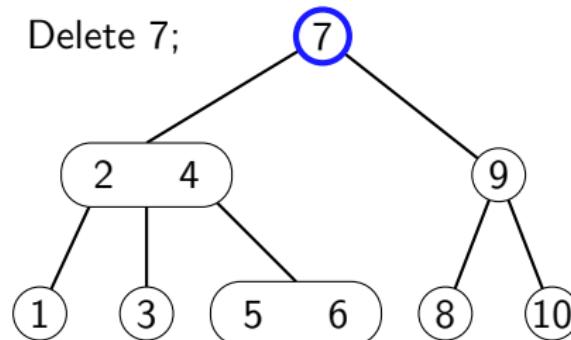


Exercise: If v is not stored in a leaf, then the **predecessor** w of v — the value just before v in sorted order — will always be in a leaf.

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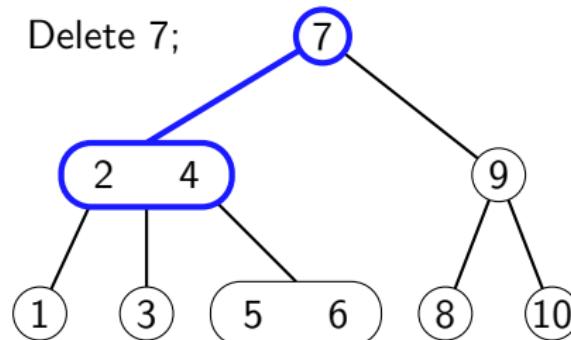


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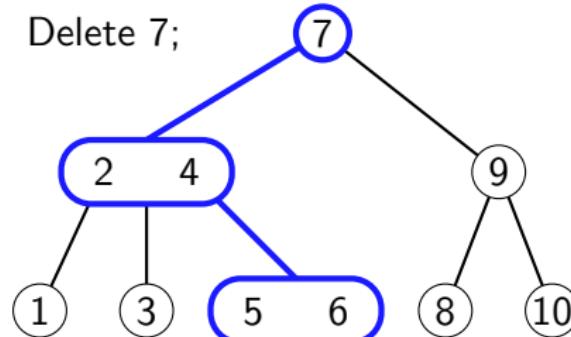


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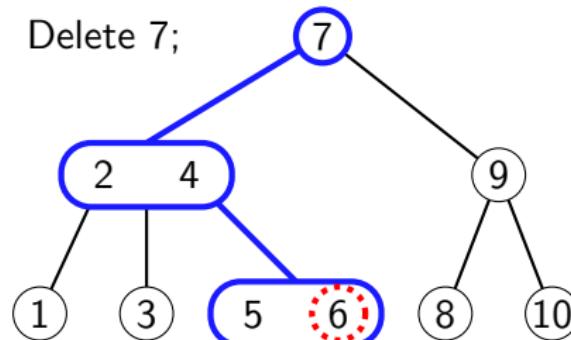


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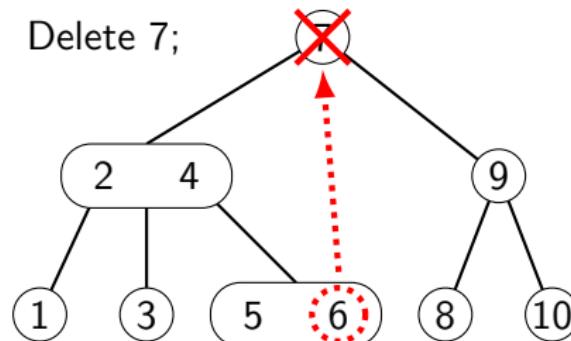


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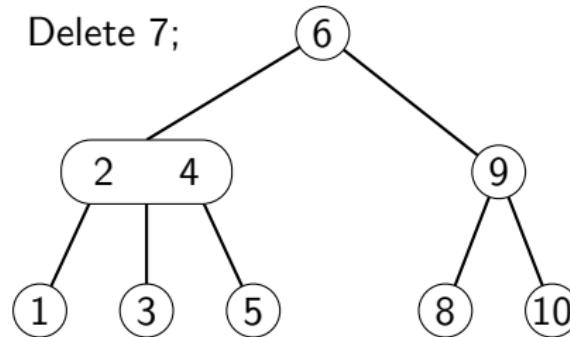


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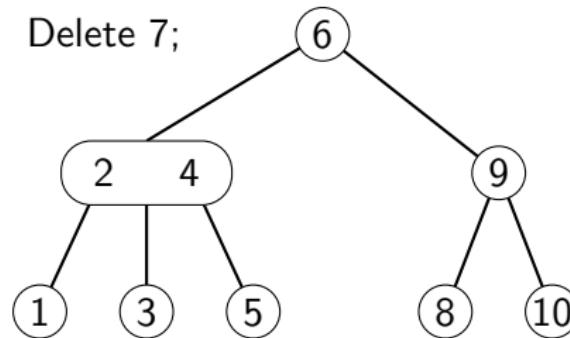


Exercise: If v is not stored in a leaf, then the **predecessor** w of v — the value just before v in sorted order — will always be in a leaf.

So we can overwrite v with w , and then delete w from its leaf — leaving the structure of the tree untouched!

Deleting from a non-leaf

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In general, this will be its own delete operation, and might require fusing/transferring 2-nodes as normal.

Summary of 2-3-4 tree operations

- **Find(v):**
 - Descend the tree recursively, using the rule that all children between x and y have values between x and y . If you reach a leaf not containing v , return **Not found**.
- **Insert(v):**
 - Apply Find(v) until reaching the leaf ℓ where v would be if it was already in the tree.
 - If ℓ is a 2-node or a 3-node, add v to ℓ .
 - Otherwise, **split** ℓ into 2-nodes and add v to the appropriate new leaf.
 - To avoid ℓ being a 4-node with a 4-node parent, split 4-nodes on the way down (including the root).
- **Delete(v):**
 - Apply Find(v) to find the vertex ℓ containing v .
 - If ℓ is not a leaf, find v 's predecessor w , overwrite v with w , and Delete(w).
 - Otherwise, if ℓ is a 3-node or a 4-node, delete v from ℓ .
 - Otherwise, if ℓ 's left or right sibling is a 3-node or 4-node, **transfer** from it to make ℓ a 3-node, then delete v .
 - Otherwise, **fuse** ℓ with its 2-node sibling to make ℓ a 4-node, then delete v .
 - To avoid ℓ being a 2-node with a 2-node parent, fuse or transfer 2-nodes on the way down (including the root).

All operations take $O(d)$ time and maintain perfect balance. Perfect balance implies that in an n -element tree, $d \in O(\log n)$ (exercise!), so we're done.

Red-black trees

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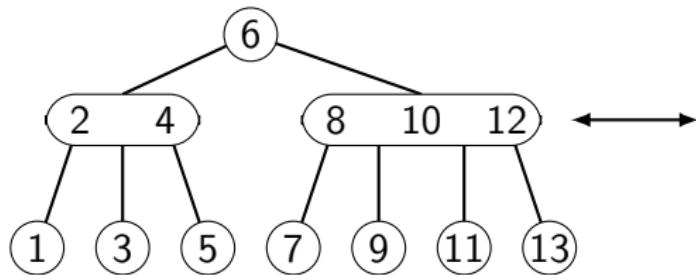
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Exception: A black node with a single red leaf child is OK.
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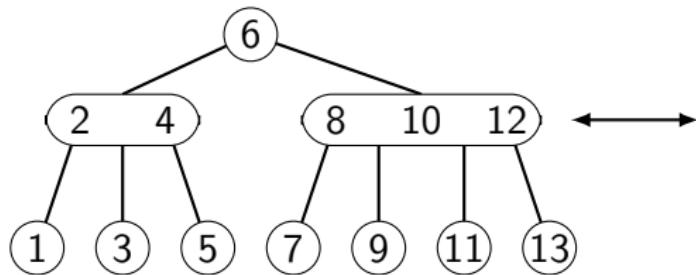


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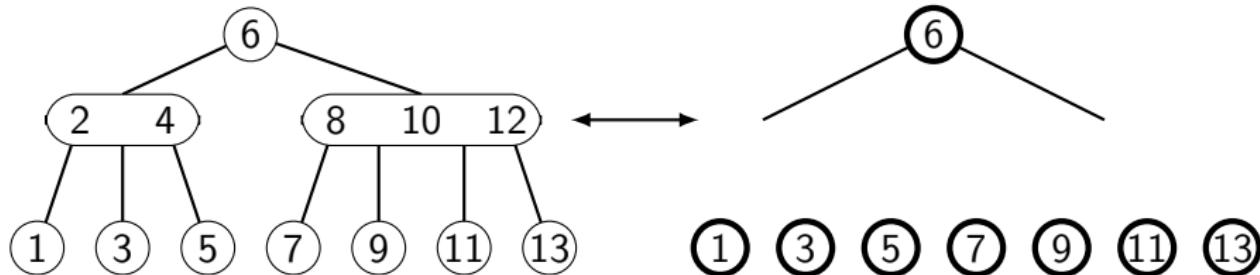


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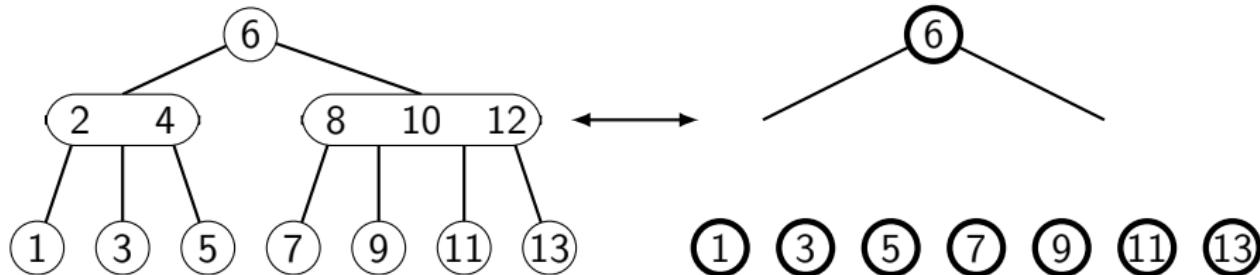


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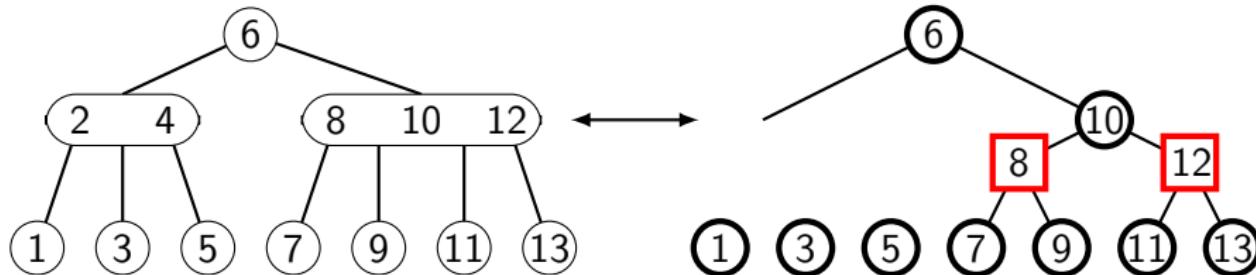


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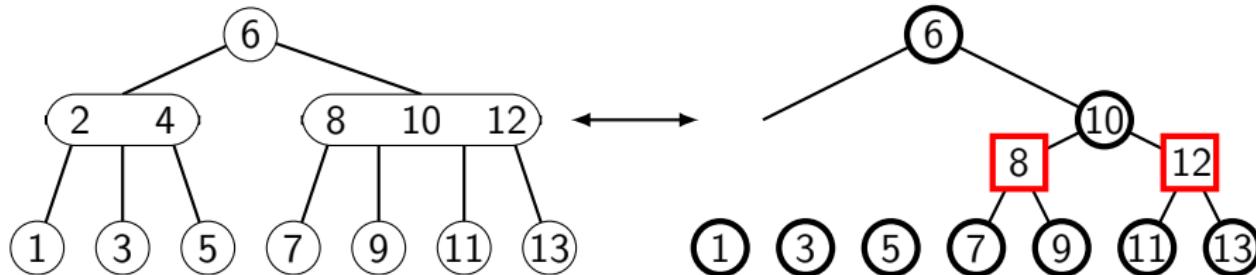


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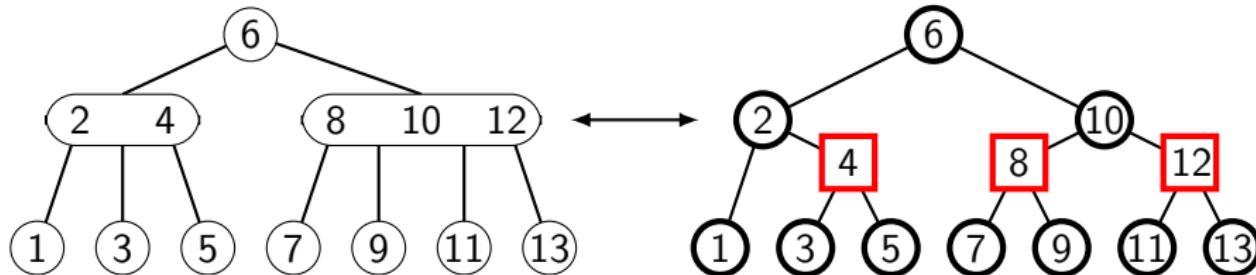


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