



CSE 332: Data Abstractions

Lecture 9: B Trees

Ruth Anderson

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Announcements

- **Project 2** – posted!
Partner selection due by 11pm Wed 10/16 *at the latest*.
- **Homework 3** – due Friday 10/18

Today

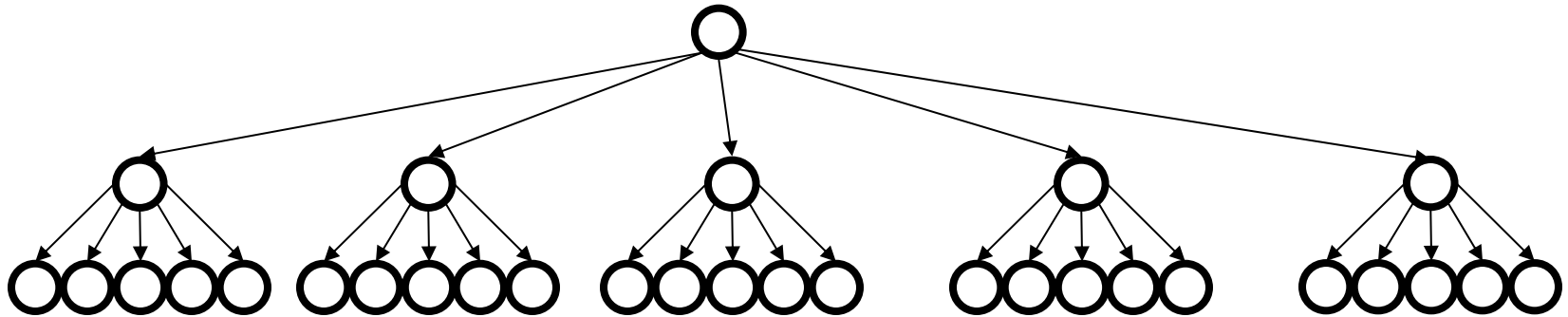
- Dictionaries
 - B-Trees

Our goal

- **Problem:** A dictionary with so much data most of it is on disk
- **Desire:** A balanced tree (logarithmic height) that is even shallower than AVL trees so that we can minimize disk accesses and exploit disk-block size
- **A key idea:** Increase the branching factor of our tree

M-ary Search Tree

- Build some sort of search tree with branching factor M :
 - Have an array of sorted children (**Node** [])
 - Choose M to fit snugly into a disk block (1 access for array)

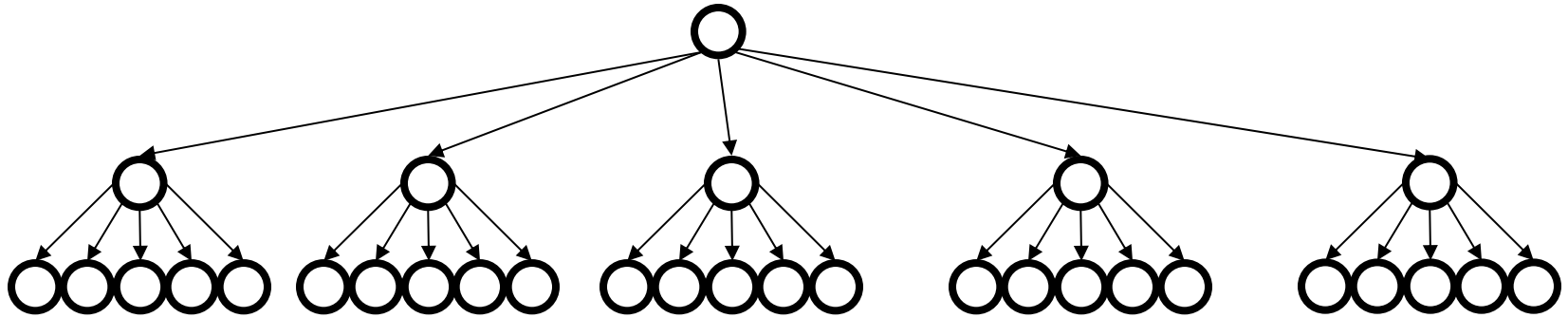


Perfect tree of height h has $(M^{h+1}-1)/(M-1)$ nodes (textbook, page 4)

What is the **height** of this tree?

What is the worst case running time of **find**?

M-ary Search Tree



- # hops for `find`?
 - If we have a balanced M-ary tree:
 - Approx. $\log_M n$ hops instead of $\log_2 n$ (for balanced BST)
 - Example: $M = 256 (=2^8)$ and $n = 2^{40}$ that's 5 hops instead of 40 hops
- Sounds good, but how do we decide which branch to take?
 - Binary tree: Less than/greater than node value?
 - M-ary: In range 1? In range 2? In range 3?... In range M?
- Runtime of `find` if balanced: $O(\log_2 M \log_M n)$
 - $\log_M n$ is the height we traverse.
 - $\log_2 M$: At each step, find the correct child branch to take using binary search among the M options!

Questions about *M*-ary search trees

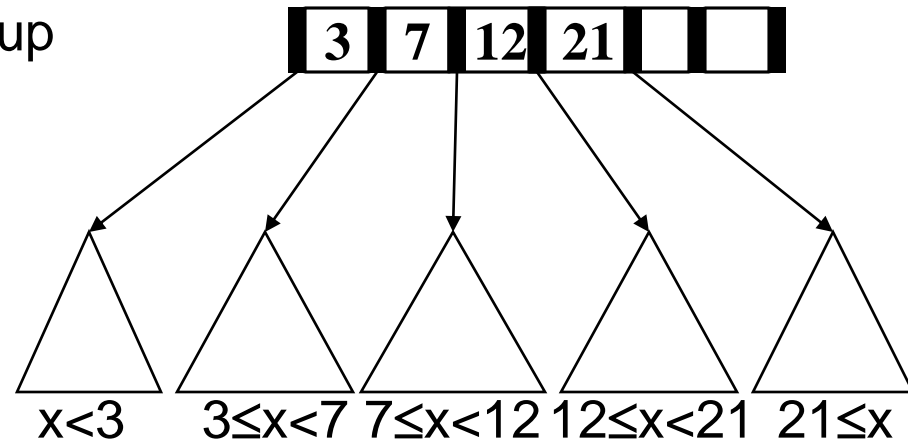
- What should the **order** property be?
- How would you **rebalance** (ideally without more disk accesses)?
- Storing **real data** at inner-nodes (like we do in a BST) seems kind of wasteful...
 - To access the node, will have to load the **data** from disk, even though most of the time we won't use it!!
 - Usually we are just “passing through” a node on the way to the value we are actually looking for.

So let's use the branching-factor idea, but for a **different kind of balanced tree**:

- **Not** a binary *search tree*
- But still logarithmic height for any $M > 2$

B+ Trees (we and the book say “B Trees”)

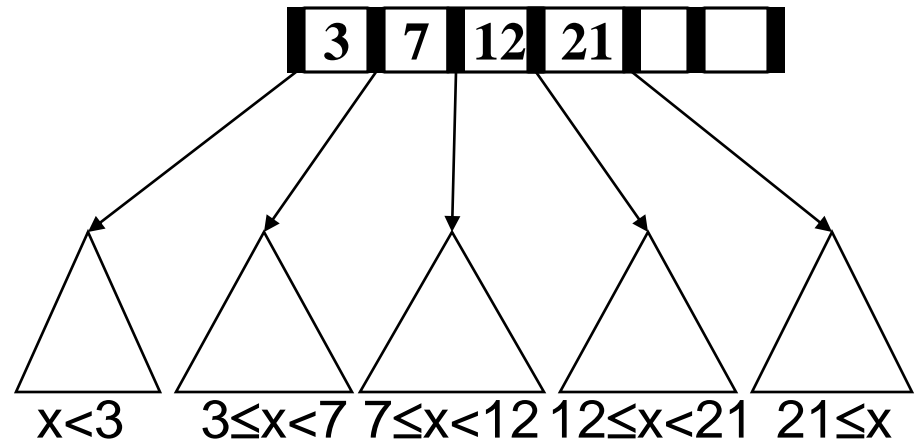
- Two types of nodes: **internal nodes** & **leaves**
- Each **internal node** has room for up to $M-1$ keys and M children
 - No other data; **all data at the leaves!**
- **Order property:**
Subtree **between** keys a and b contains only data that is $\geq a$ and $< b$ (notice the \geq)
- **Leaf** nodes have up to L sorted data items
- As usual, we'll ignore the “along for the ride” data in our examples
 - Remember no data at non-leaves



Remember:

- **Leaves** store data
- **Internal nodes** are ‘signposts’

Find



- Different from BST in that we don't store data at internal nodes
- But **find** is still an easy root-to-leaf recursive algorithm
 - At each internal node do binary search on (up to) $M-1$ keys to find the branch to take
 - At the leaf do binary search on the (up to) L data items
- But to get logarithmic running time, we need a balance condition...

Structure Properties

- **Root** (special case)
 - If tree has $\leq L$ items, root is a leaf (occurs when starting up, otherwise unusual)
 - Else has between 2 and M children
- **Internal nodes**
 - Have between $\lceil M/2 \rceil$ and M children, i.e., **at least half full**
- **Leaf nodes**
 - All leaves at the same depth
 - Have between $\lceil L/2 \rceil$ and L data items, i.e., **at least half full**

Any $M > 2$ and L will work, but:

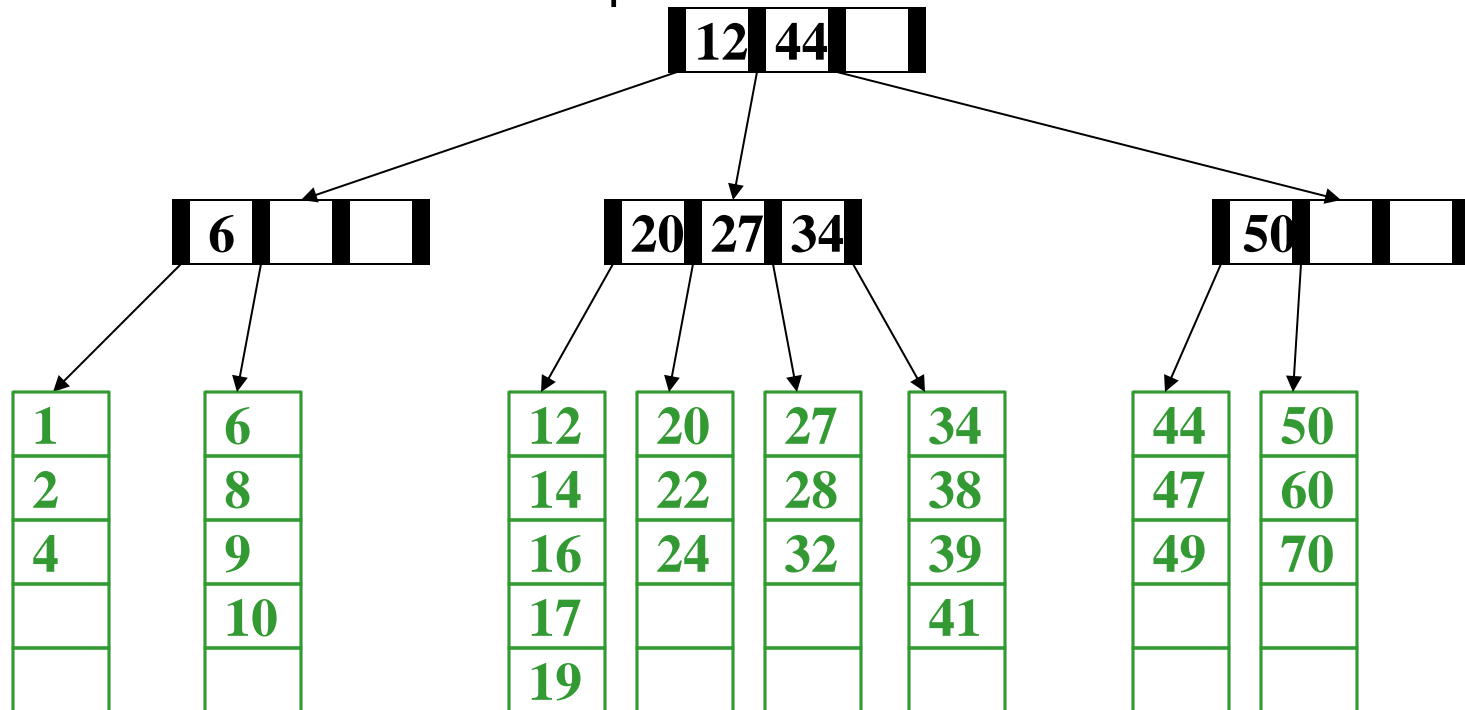
We pick M and L **based on disk-block size**

Note on notation: Inner nodes drawn horizontally, leaves vertically to distinguish. Include empty cells

Example

Suppose $M=4$ (max # pointers in **internal node**)
and $L=5$ (max # data items at **leaf**)

- All **internal nodes** have at least 2 children
- All **leaves** have at least 3 data items (only showing keys)
- All **leaves** at same depth



Balanced enough

Not hard to show height h is logarithmic in number of data items n

- Let $M > 2$ (if $M = 2$, then a list tree is legal – no good!)
- Because all nodes are at least half full (except root may have only 2 children) and all leaves are at the same level, the minimum number of data items n for a height $h > 0$ tree is...

$$n \geq \underbrace{2 \lceil M/2 \rceil^{h-1}}_{\text{minimum number of leaves}} \underbrace{\lceil L/2 \rceil}_{\text{minimum data per leaf}}$$

Example: B-Tree vs. AVL Tree

Suppose we have 100,000,000 items

- Maximum height of AVL tree?
- Maximum height of B tree with $M=128$ and $L=64$?

Example: B-Tree vs. AVL Tree

Suppose we have 100,000,000 items

- **Maximum height of AVL tree?**
 - Recall $S(h) = 1 + S(h-1) + S(h-2)$
 - lecture7.xlsx reports: **37**
- **Maximum height of B tree** with $M=128$ and $L=64$?
 - Recall $(2 \lceil M/2 \rceil^{h-1}) \lceil L/2 \rceil$
 - lecture9.xlsx reports: **5** (and 4 is more likely)
 - Also not difficult to compute via algebra

Disk Friendliness

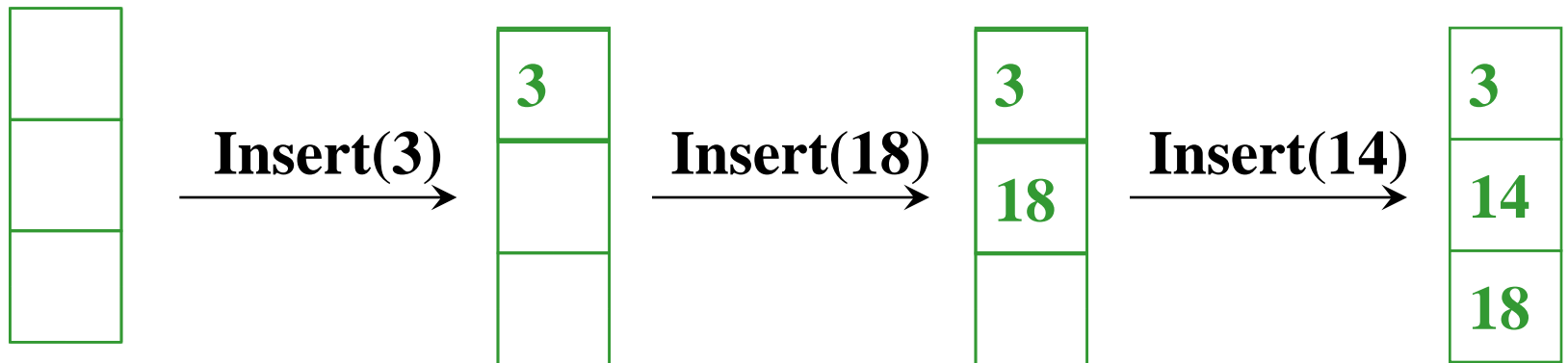
What makes B trees so disk friendly?

- Many keys stored in one **internal node**
 - All brought into memory in one disk access
 - *IF* we pick M wisely
 - Makes the binary search over $M-1$ keys totally worth it (insignificant compared to disk access times)
- **Internal nodes** contain only keys
 - Any **find** wants only one data item; wasteful to load unnecessary items with internal nodes
 - So only bring one **leaf** of data items into memory
 - Data-item size doesn't affect what M is

Maintaining balance

- So this seems like a great data structure (and it is)
- But we haven't implemented the other dictionary operations yet
 - **insert**
 - **delete**
- As with AVL trees, the hard part is maintaining structure properties
 - Example: for **insert**, there might not be room at the correct leaf

Building a B-Tree (insertions)

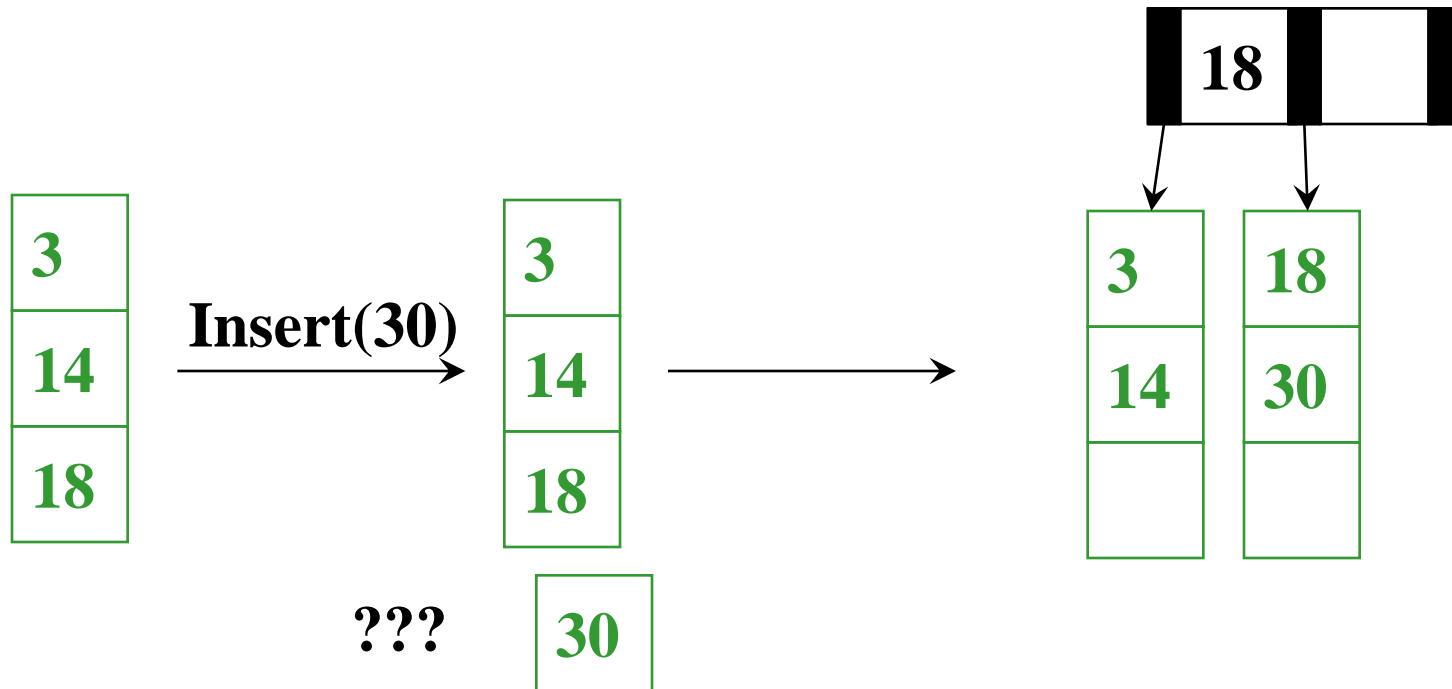


The empty B-Tree (the **root** will be a leaf at the beginning)

Just need to keep data in order

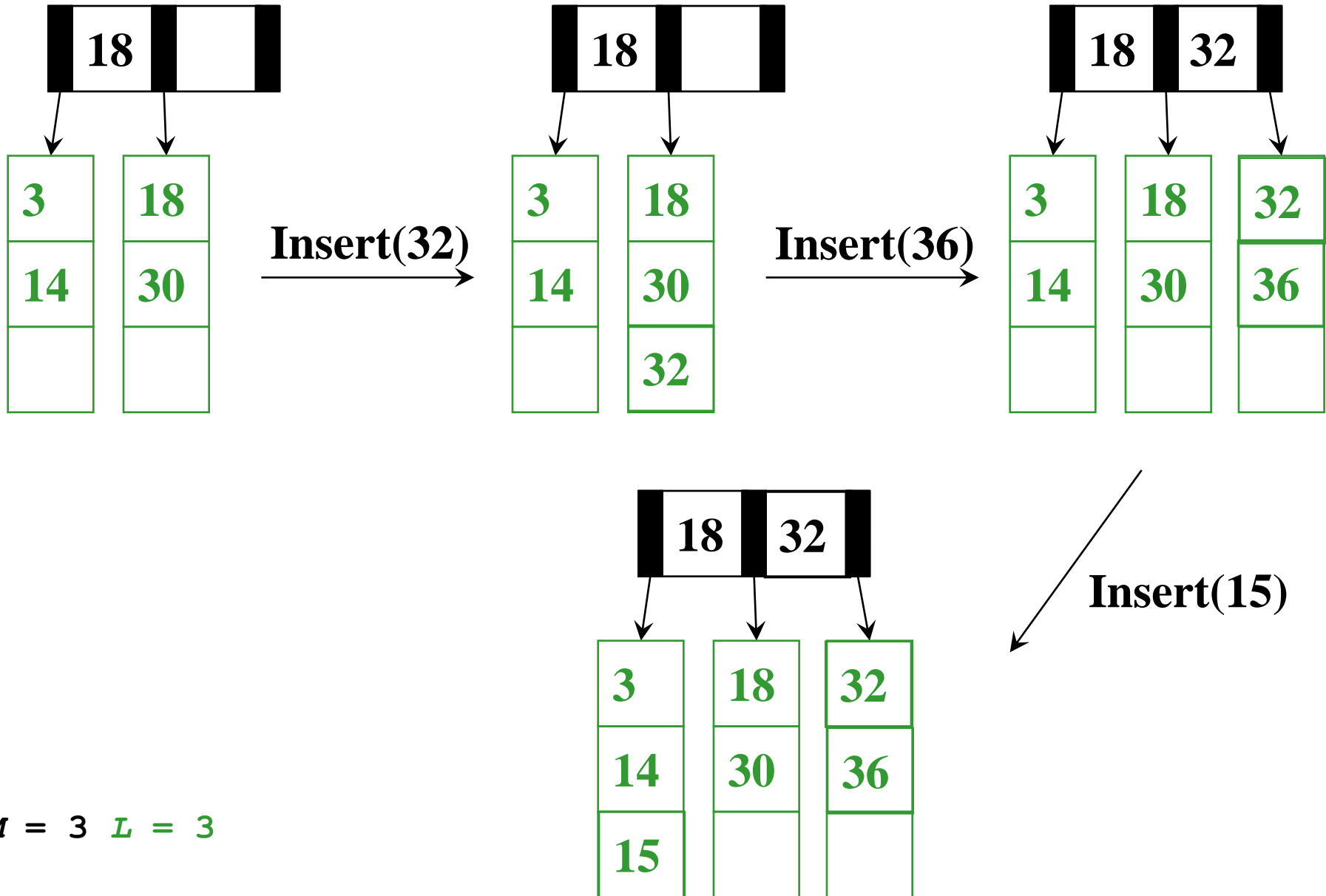
$$M = 3 \quad L = 3$$

$M = 3$ $L = 3$

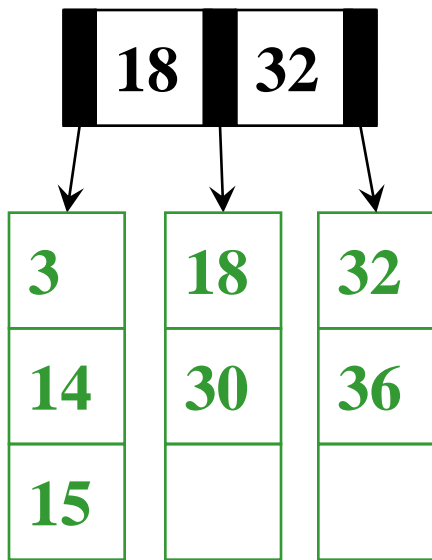


- When we ‘overflow’ a **leaf**, we split it into 2 leaves
- Parent gains another child
- If there is no parent (like here), we create one; how do we pick the key shown in it?
 - Smallest element in right tree

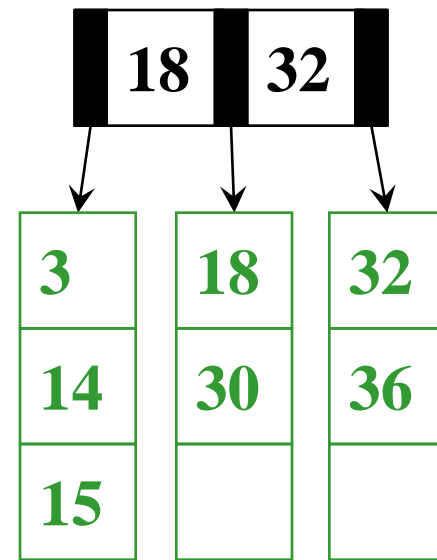
Split **leaf** again



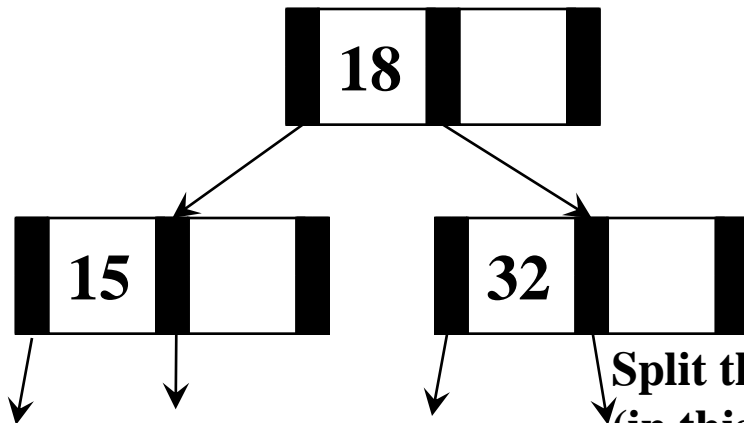
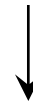
$M = 3$ $L = 3$



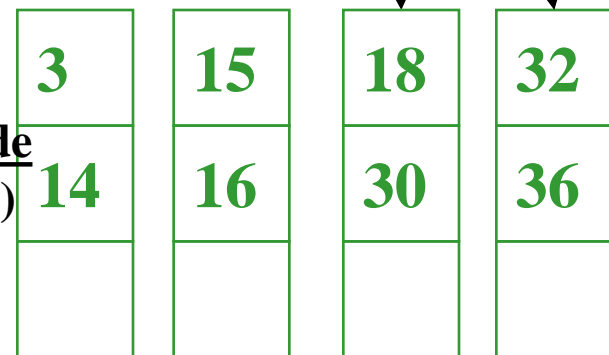
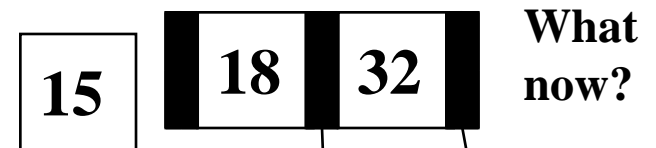
Insert(16)

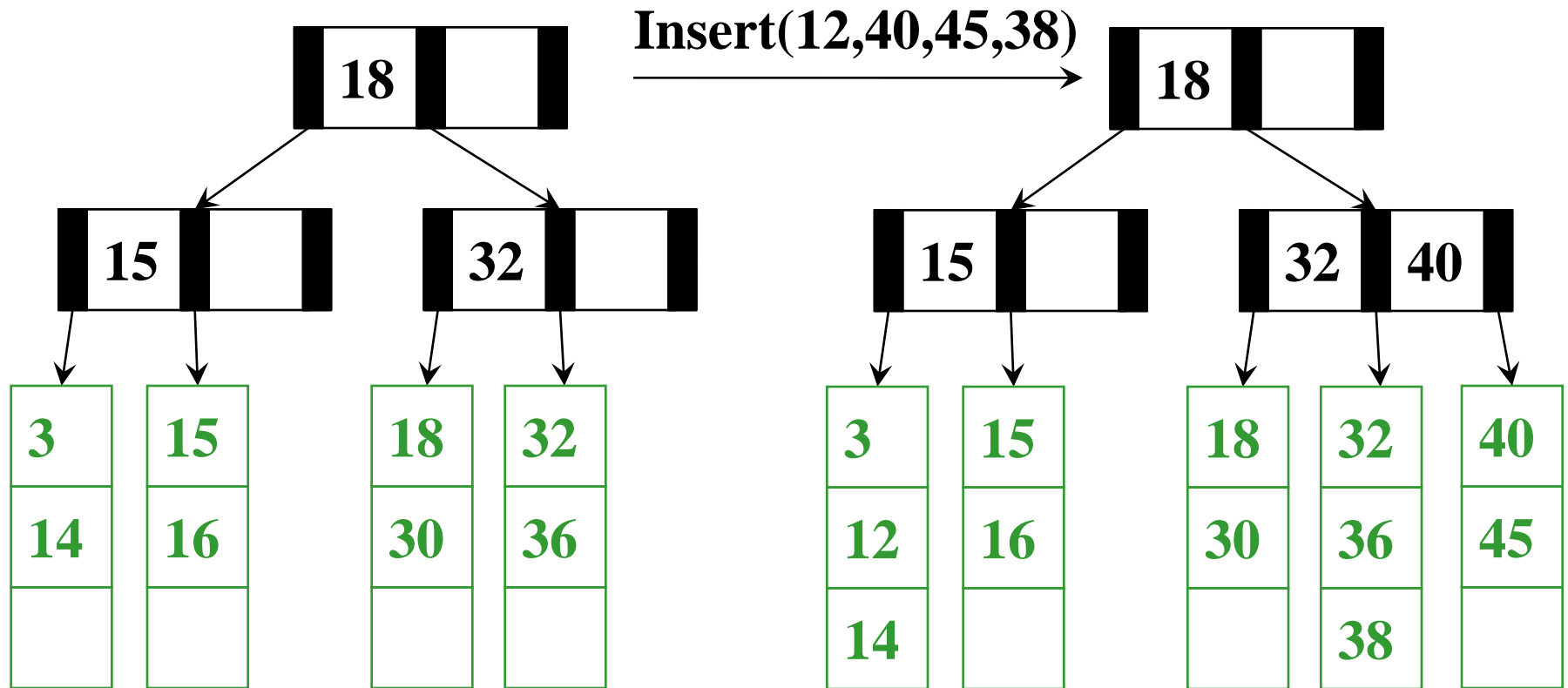


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Split the internal node
(in this case, the **root**)





$M = 3$ $L = 3$

Note: Given the **leaves** and the structure of the tree, we can always fill in internal node keys; ‘the smallest value in my right branch’

Insertion Algorithm

1. Insert the data in its **leaf** in sorted order
2. If the **leaf** now has $L+1$ items, *overflow!*
 - Split the **leaf** into two nodes:
 - Original **leaf** with $\lceil (L+1) / 2 \rceil$ smaller items
 - New **leaf** with $\lfloor (L+1) / 2 \rfloor = \lceil L/2 \rceil$ larger items
 - Attach the new child to the parent
 - Adding new key to parent in sorted order
3. If step (2) caused the parent to have $M+1$ children, *overflow!*
 - ...

Insertion algorithm continued

3. If an **internal node** has $M+1$ children
 - Split the **node** into **two nodes**
 - Original **node** with $\lceil (M+1) / 2 \rceil$ smaller items
 - New **node** with $\lfloor (M+1) / 2 \rfloor = \lceil M/2 \rceil$ larger items
 - Attach the new child to the parent
 - Adding new key to parent in sorted order

Splitting at a node (step 3) could make the parent overflow too

- *So repeat step 3 up the tree until a node doesn't overflow*
- If the **root** overflows, make a new **root** with two children
 - This is the only case that increases the tree height

Efficiency of insert

- Find correct leaf: $O(\log_2 M \log_M n)$
- Insert in leaf: $O(L)$
- Split leaf: $O(L)$
- Split parents all the way up to root: $O(M \log_M n)$

Total: $O(L + M \log_M n)$

But it's not that bad:

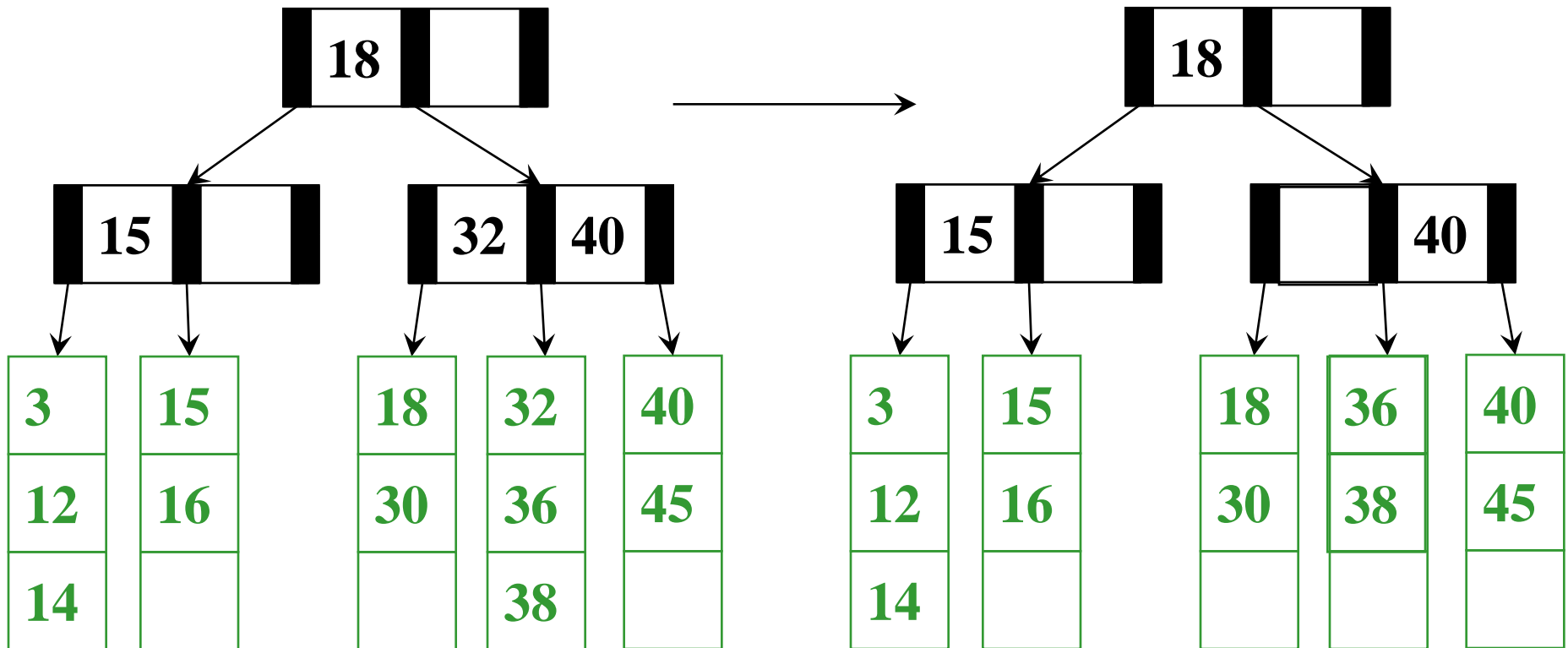
- Splits are not that common (only required when a node is FULL, M and L are likely to be large, and after a split, will be half empty)
- Splitting the **root** is extremely rare
- Remember disk accesses were the name of the game:
 $O(\log_M n)$

B-Tree Reminder: Another dictionary

- Before we talk about deletion, just keep in mind overall idea:
 - Large data sets won't fit entirely in memory
 - Disk access is slow
 - Set up tree so we do one disk access per node in tree
 - Then our goal is to keep tree shallow as possible
 - Balanced binary tree is a good start, but we can do better than $\log_2 n$ height
 - In an M-ary tree, height drops to $\log_M n$
 - Why not set M really really high? Height 1 tree...
 - Instead, set M so that each node fits in a disk block

And Now for Deletion...

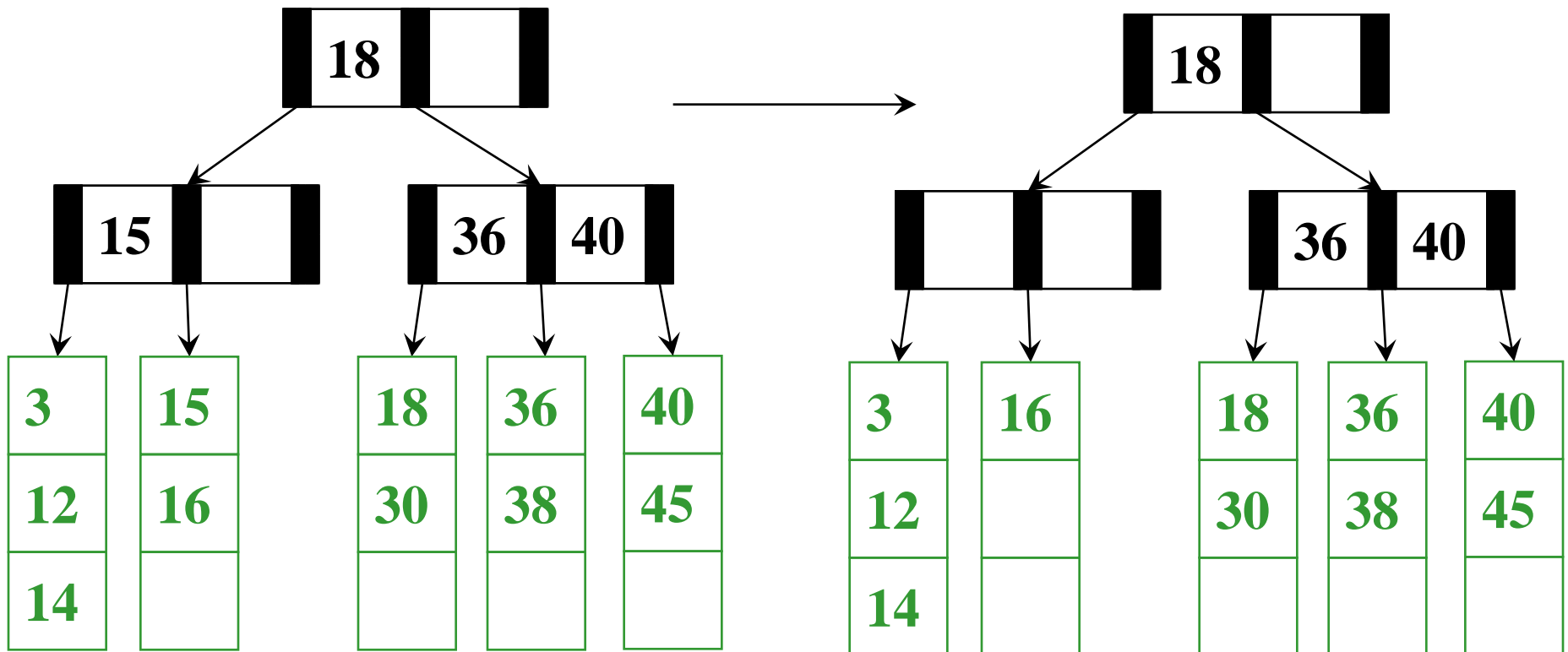
Delete(32)



Easy case: Leaf still has enough data; just remove

$M = 3$ $L = 3$

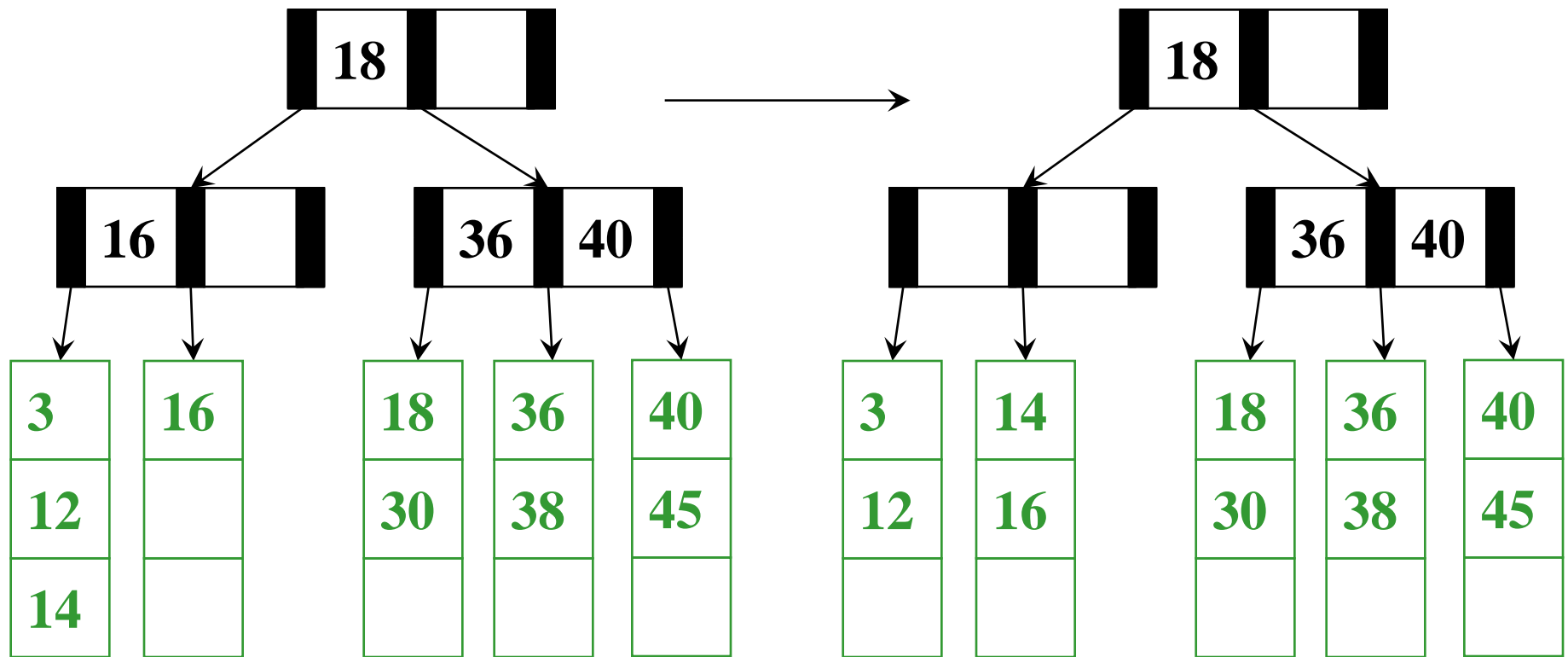
Delete(15)



Is there a problem?

$M = 3$ $L = 3$

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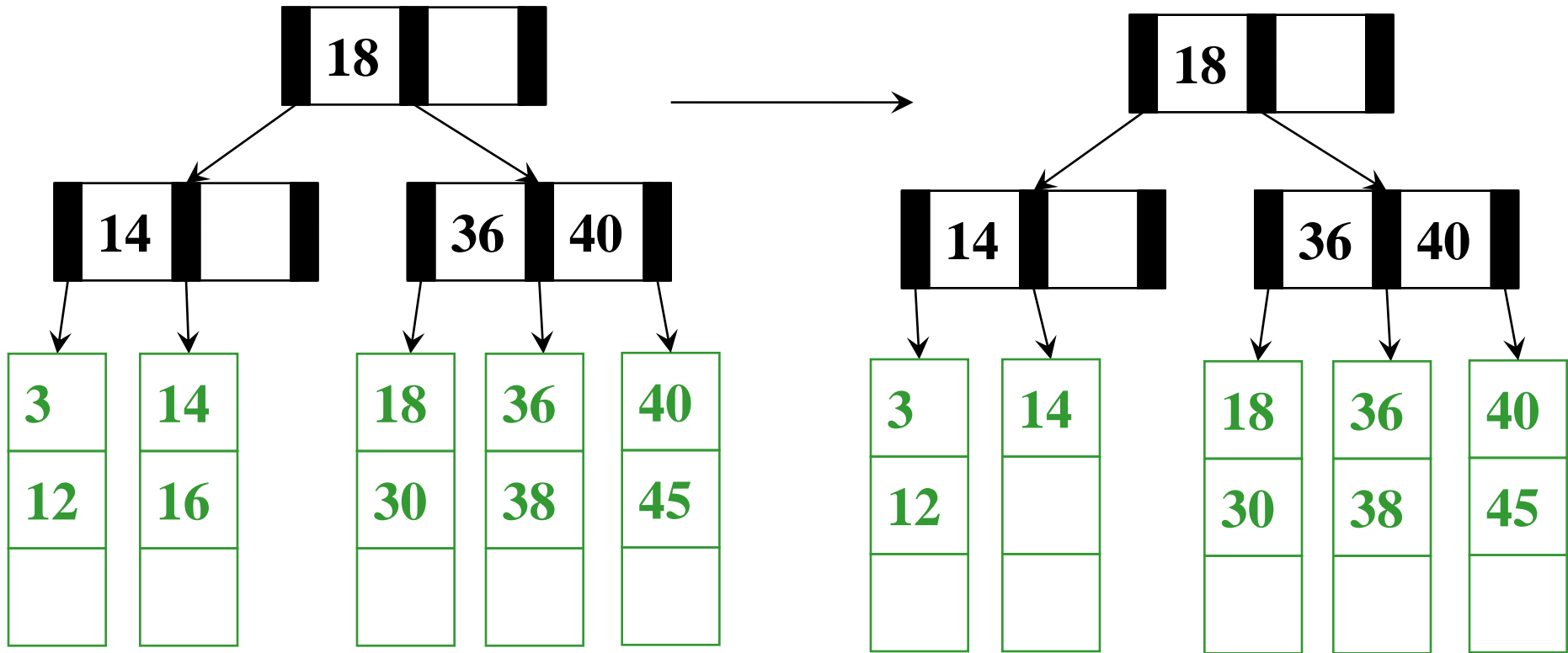


$M = 3$ $L = 3$

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Adopt from neighbor!

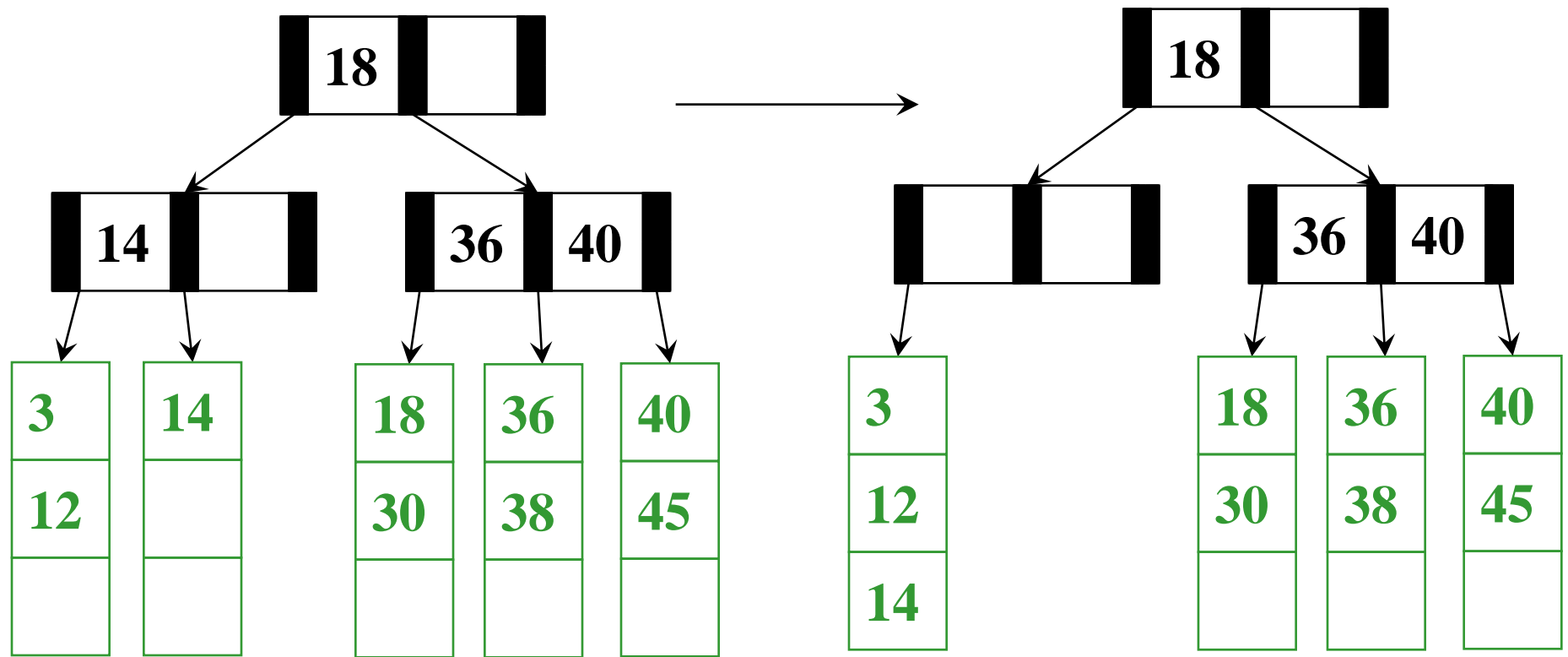
Delete(16)



$M = 3$ $L = 3$

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Is there a problem?

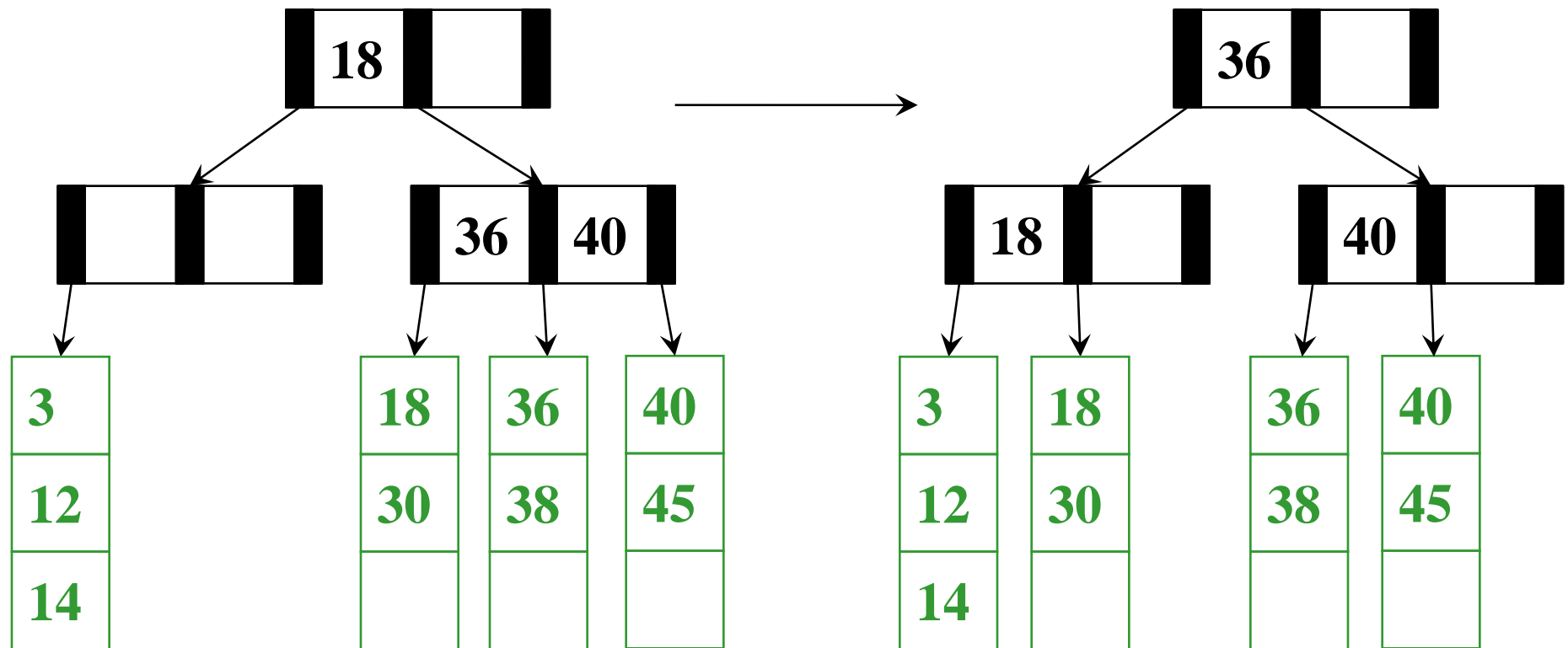


Merge with neighbor!

$M = 3$ $L = 3$

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But hey, Is there a problem? 30

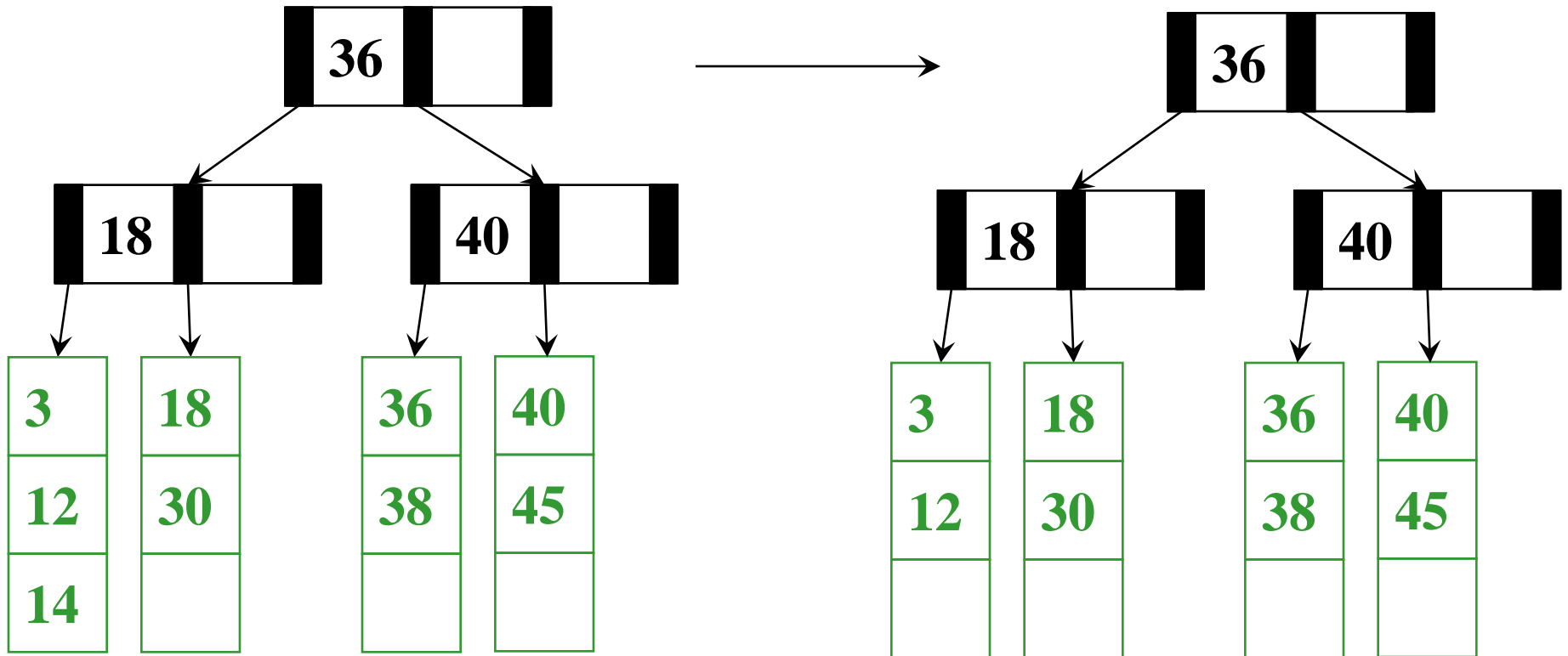


$M = 3$ $L = 3$

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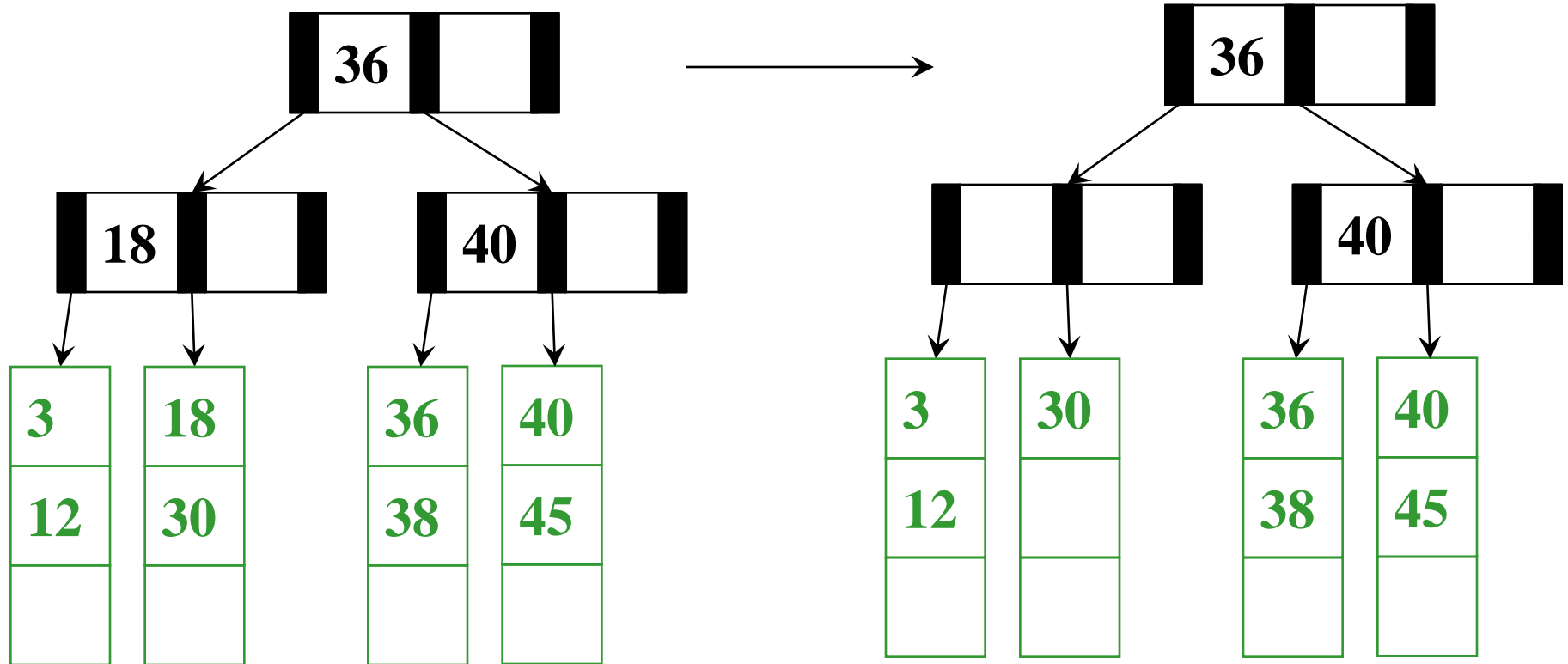
Adopt from neighbor!

Delete(14)



$M = 3$ $L = 3$

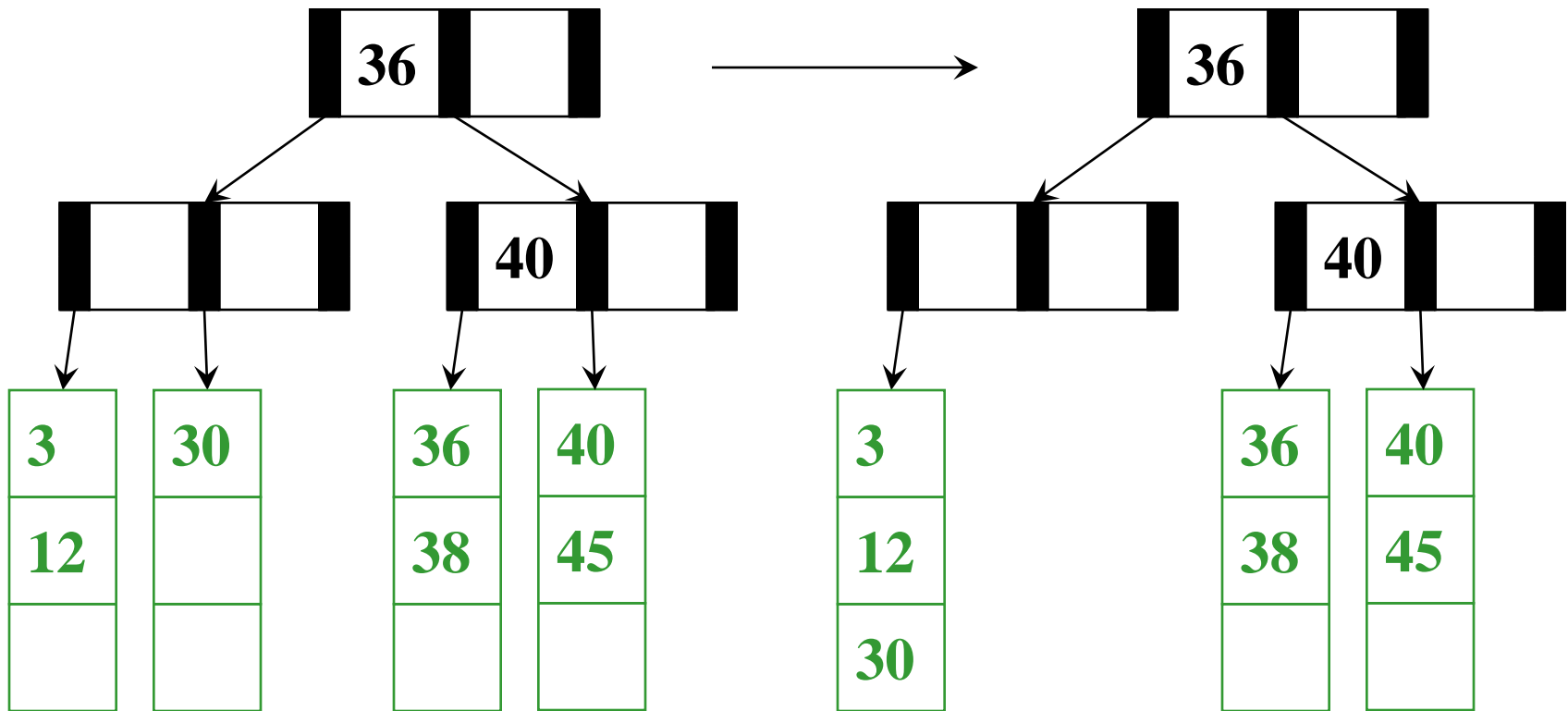
Delete(**18**)



$M = 3$ $L = 3$

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Is there a problem?

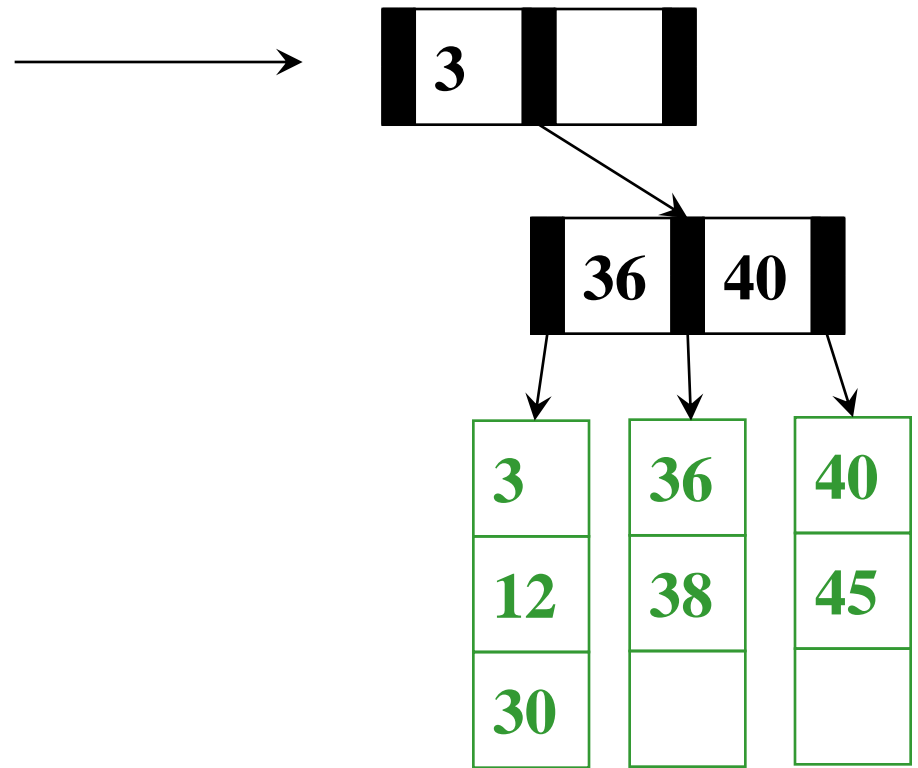
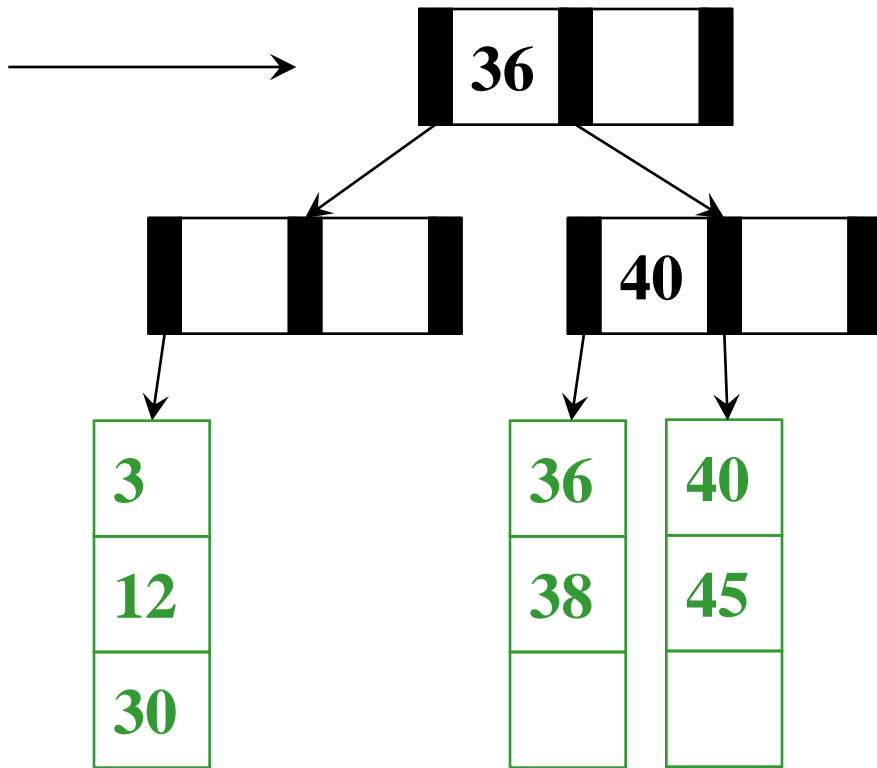


$M = 3$ $L = 3$

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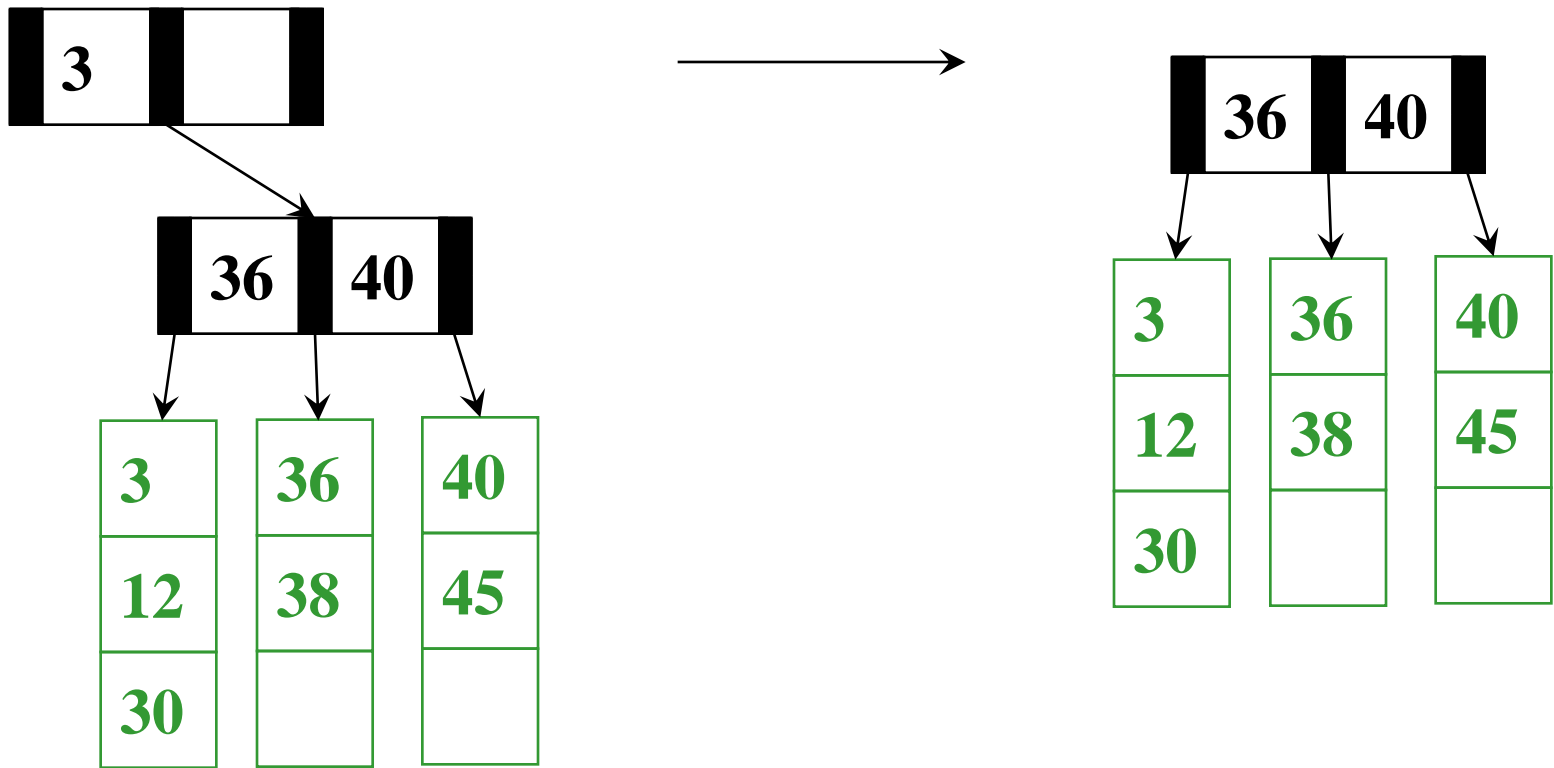
Merge with neighbor!

But hey, Is there a problem?



$M = 3$ $L = 3$

Merge with neighbor!



$M = 3$ $L = 3$

Pull out the root!

Deletion Algorithm, part 1

1. Remove the data from its leaf
2. If the leaf now has $\lceil L/2 \rceil - 1$, *underflow!*
 - If a neighbor has $> \lceil L/2 \rceil$ items, *adopt* and update parent
 - Else *merge* node with neighbor
 - Guaranteed to have a legal number of items
 - Parent now has one less node
3. If step (2) caused the parent to have $\lceil M/2 \rceil - 1$ children, *underflow!*
 - ...

Deletion algorithm (continued)

3. If an internal node has $\lceil M/2 \rceil - 1$ children
 - If a neighbor has $> \lceil M/2 \rceil$ items, *adopt* and update parent
 - Else *merge* node with neighbor
 - Guaranteed to have a legal number of items
 - Parent now has one less node, may need to continue up the tree

If we merge all the way up through the root, that's fine unless the root went from 2 children to 1

- In that case, delete the root and make child the root
- This is the only case that decreases tree height

Worst-Case Efficiency of Delete

- Find correct leaf: $O(\log_2 M \log_M n)$
- Remove from leaf: $O(L)$
- Adopt from or merge with neighbor: $O(L)$
- Adopt or merge all the way up to root: $O(M \log_M n)$

Total: $O(L + M \log_M n)$

But it's not that bad:

- Merges are not that common
- Disk accesses are the name of the game: $O(\log_M n)$

Insert vs delete comparison

Insert

- Find correct leaf: $O(\log_2 M \log_M n)$
- Insert in leaf: $O(L)$
- Split leaf: $O(L)$
- Split parents all the way up to root: $O(M \log_M n)$

Delete

- Find correct leaf: $O(\log_2 M \log_M n)$
- Remove from leaf: $O(L)$
- Adopt/merge from/with neighbor leaf: $O(L)$
- Adopt or merge all the way up to root: $O(M \log_M n)$

B Trees in Java?

For most of our data structures, we have encouraged writing high-level, reusable code, such as in Java with generics

It is worthwhile to know enough about “how Java works” to understand why this is probably a bad idea for B trees

- If you just want a balanced tree with worst-case logarithmic operations, no problem
 - If $M=3$, this is called a 2-3 tree
 - If $M=4$, this is called a 2-3-4 tree
- Assuming our goal is efficient number of disk accesses
 - Java has many advantages, but it wasn't designed for this

The key issue is extra *levels of indirection*...

Naïve approach in Java

Even if we assume data items have `int` keys, you cannot get the data representation you want for “really big data”

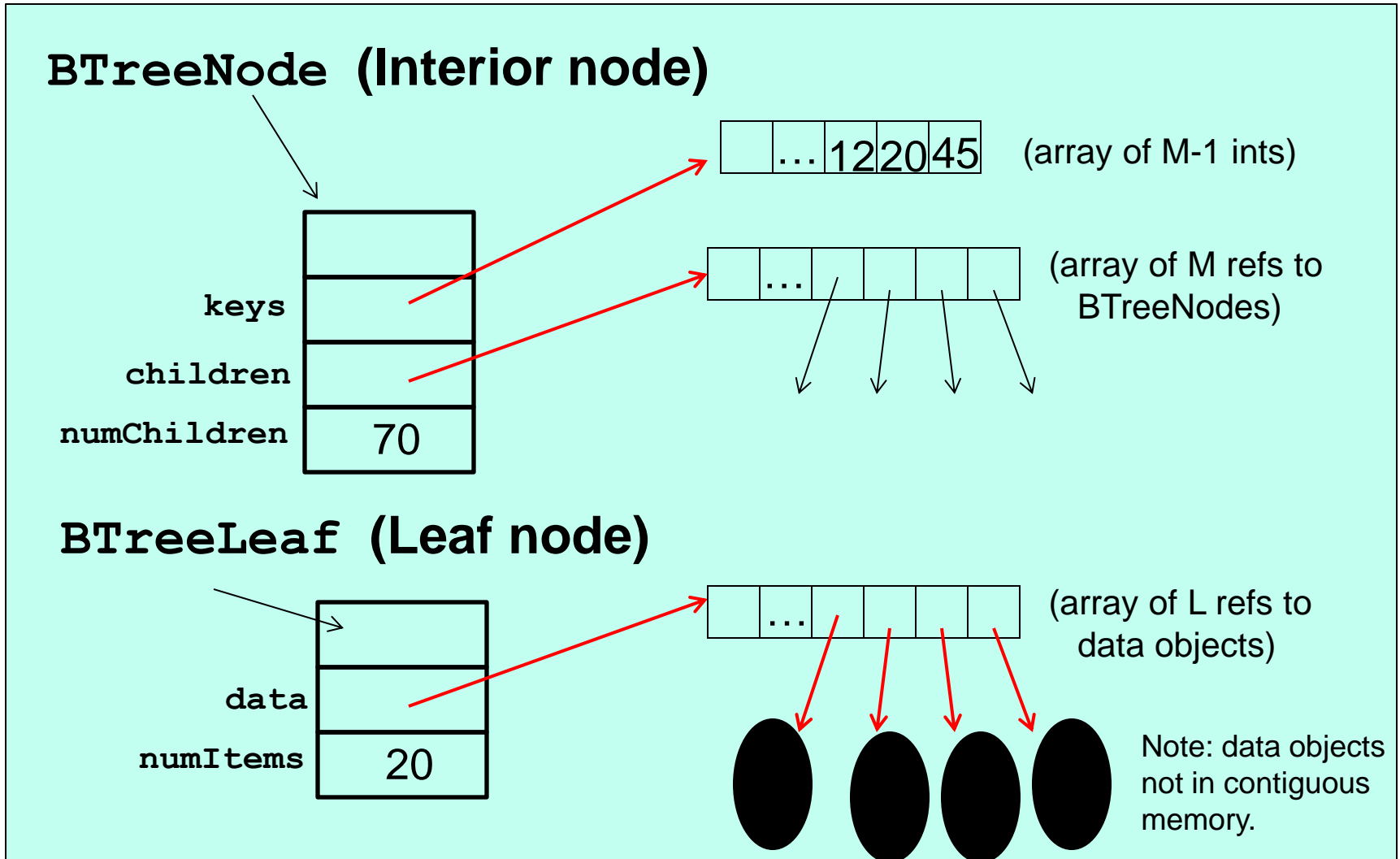
```
interface Keyed {
    int getKey();
}

class BTreeNode<E implements Keyed> {
    static final int M = 128;
    int[] keys = new int[M-1];
    BTreeNode<E>[] children = new BTreeNode[M];
    int numChildren = 0;
    ...
}

class BTreeLeaf<E implements Keyed> {
    static final int L = 32;
    E[] data = (E[])new Object[L];
    int numItems = 0;
    ...
}
```

All the **red** references indicate “unnecessary” indirection that might be avoided in another programming language.

What that looks like in Java



The moral

- The whole idea behind B trees was to keep related data in contiguous memory
- But that's “the best you can do” in Java
 - Again, the advantage is generic, reusable code
 - But for your performance-critical web-index, not the way to implement your B-Tree for terabytes of data
- Other languages (e.g., C++) have better support for “flattening objects into arrays”
- Levels of indirection matter!

Conclusion: Balanced Trees

- *Balanced* trees make good dictionaries because they guarantee logarithmic-time **find**, **insert**, and **delete**
 - Essential and beautiful computer science
 - But only if you can maintain balance within the time bound
- **AVL trees** maintain balance by tracking height and allowing all children to differ in height by at most 1
- **B trees** maintain balance by keeping nodes at least half full and all leaves at same height
- Other great balanced trees (see text; worth knowing they exist)
 - **Red-black trees**: all leaves have depth within a factor of 2
 - **Splay trees**: self-adjusting; amortized guarantee; no extra space for height information