Introduction to Database Systems
CSE 444

Lecture 15: Data Storage and Indexes

Where We Are

- How to use a DBMS as a:
  - Data analyst: SQL, SQL, SQL,…
  - Application programmer: JDBC, XML,…
  - Database administrator: tuning, triggers, security
  - Massive-scale data analyst: Pig/MapReduce
- How DBMSs work:
  - Transactions
  - Data storage and indexing
  - Query execution
- Databases as a service

Outline

- Storage model
- Index structures (Section 14.1)
  - [Old edition: 13.1 and 13.2]
- B-trees (Section 14.2)
  - [Old edition: 13.3]

Storage Model

- DBMS needs spatial and temporal control over storage
  – Spatial control for performance
  – Temporal control for correctness and performance
    - Solution: Buffer manager inside DBMS (see past lectures)

- For spatial control, two alternatives
  – Use “raw” disk device interface directly
  – Use OS files

Spatial Control
Using “Raw” Disk Device Interface

- **Overview**
  - DBMS issues low-level storage requests directly to disk device
- **Advantages**
  - DBMS can ensure that important queries access data sequentially
  - Can provide highest performance
- **Disadvantages**
  - Requires devoting entire disks to the DBMS
  - Reduces portability as low-level disk interfaces are OS specific
  - Many devices are in fact “virtual disk devices”

Spatial Control Using OS Files

- **Overview**
  - DBMS creates one or more very large OS files
- **Advantages**
  - Allocating large file on empty disk can yield good physical locality
- **Disadvantages**
  - OS can limit file size to a single disk
  - OS can limit the number of open file descriptors
  - But these drawbacks have mostly been overcome by modern OSs

Commercial Systems

- Most commercial systems offer both alternatives
  - Raw device interface for peak performance
  - OS files more commonly used
- In both cases, we end-up with a DBMS file abstraction implemented on top of OS files or raw device interface

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Database File Types

The data file can be one of:

- Heap file
  - Set of records, partitioned into blocks
  - Unsorted
- Sequential file
  - Sorted according to some attribute(s) called *key*

"key" here means something else than "primary key"

Index

- A (possibly separate) file, that allows fast access to records in the data file given a search key
- The index contains (key, value) pairs:
  - The key = an attribute value
  - The value = either a pointer to the record, or the record itself

"key" (aka "search key") again means something else

Index Classification

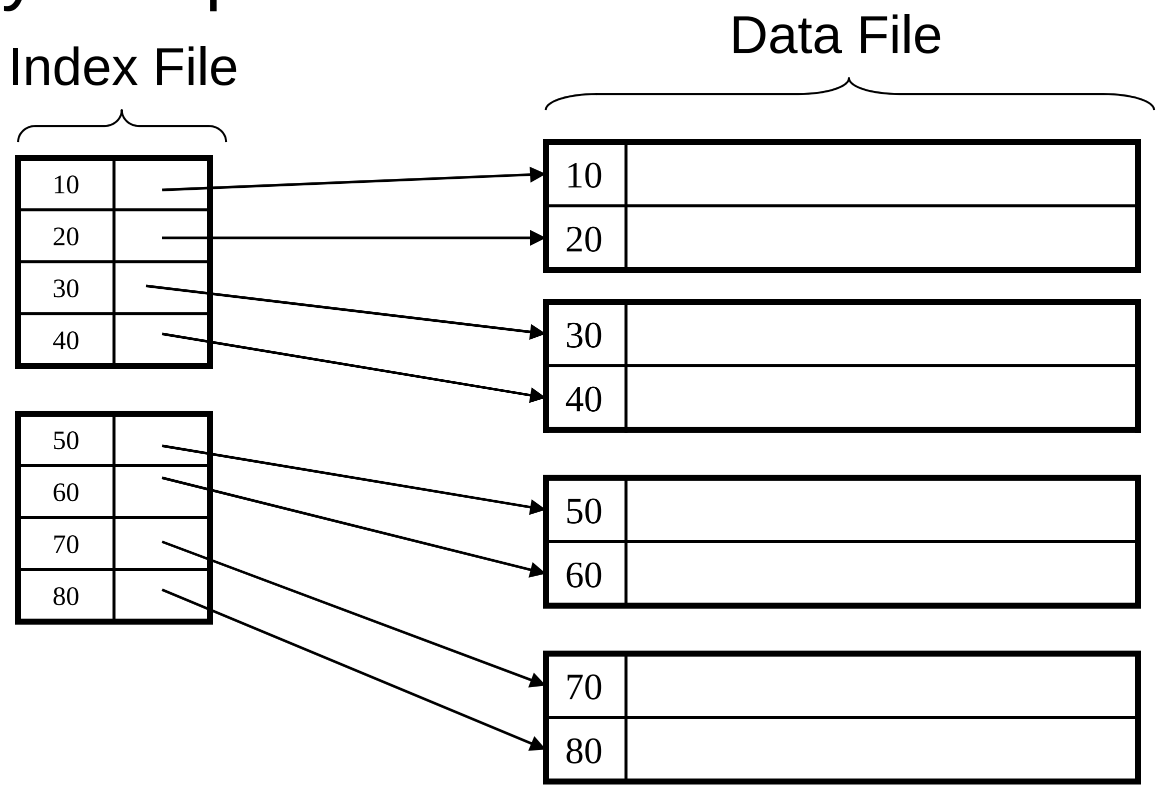
- **Clustered/unclustered**
  - Clustered = records close in index are close in data
  - Unclustered = records close in index may be far in data
- **Primary/secondary**
  - Meaning 1:
    - Primary = is over attributes that include the primary key
    - Secondary = otherwise
  - Meaning 2: means the same as clustered/unclustered
- **Organization**: B+ tree or Hash table

Clustered/Unclustered

- Clustered
  - Index determines the location of indexed records
  - Typically, clustered index is one where values are data records (but not necessary)
- Unclustered
  - Index cannot reorder data, does not determine data location
  - In these indexes: value = pointer to data record

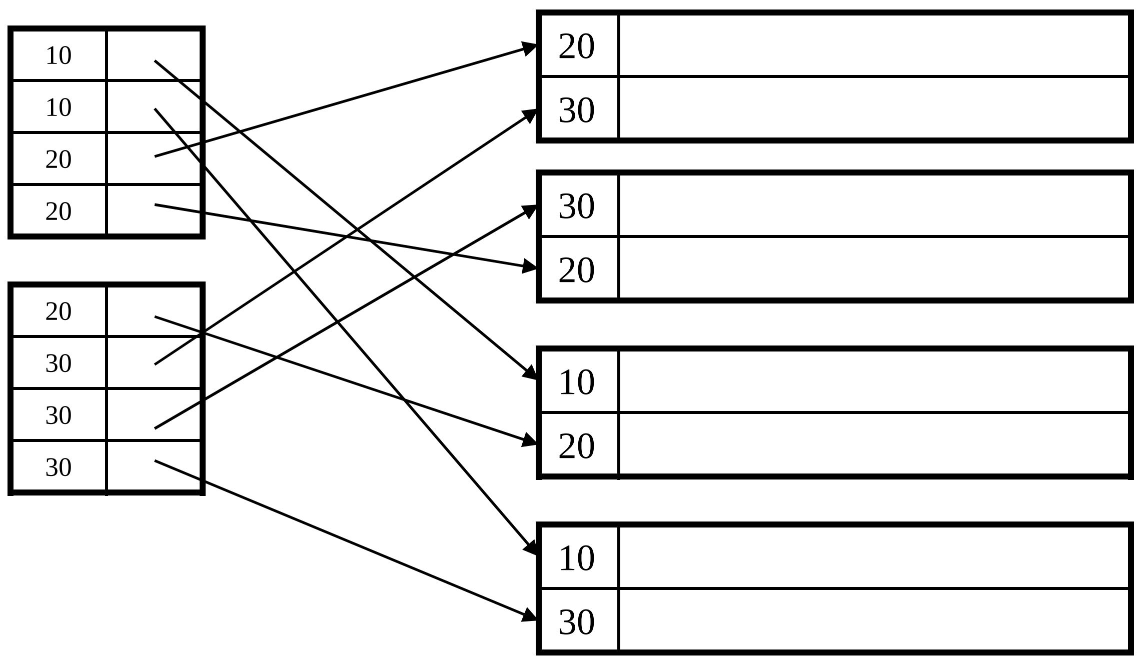
Clustered Index

- File is sorted on the index attribute
- Only one per table

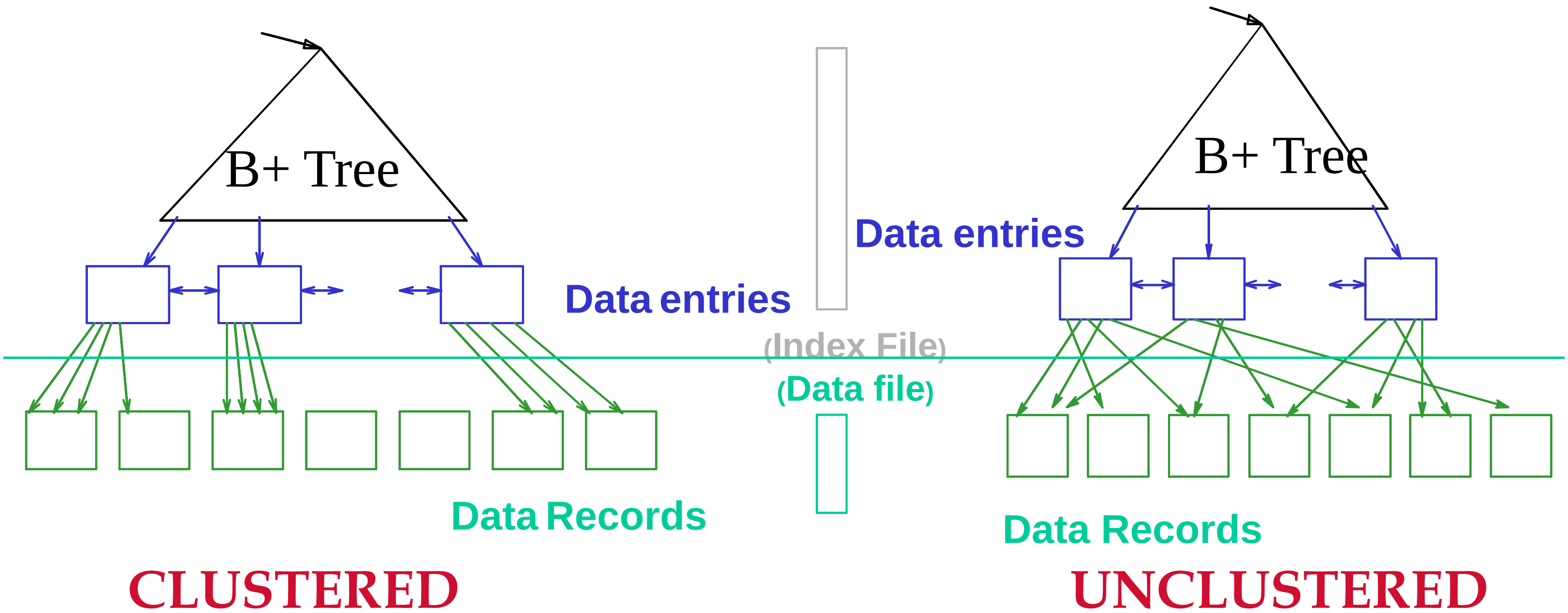


Unclustered Index

- Several per table



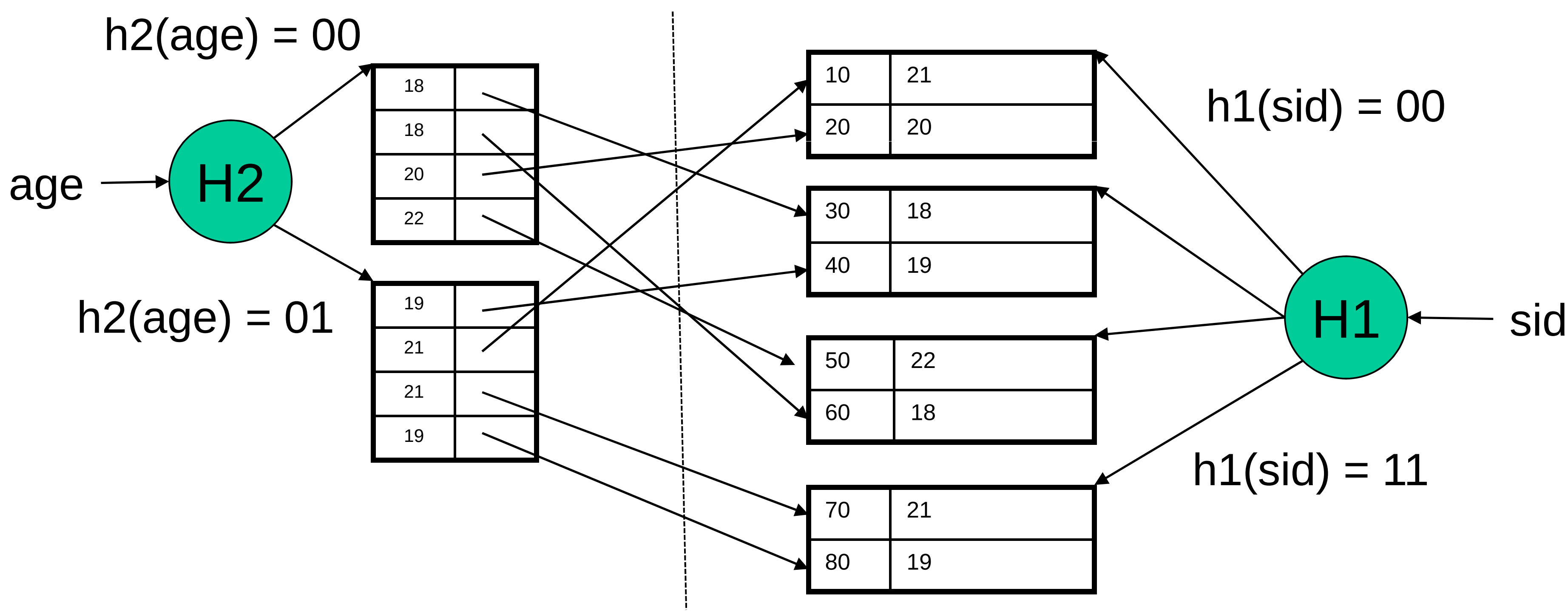
Clustered vs. Unclustered Index



- More commonly, in a clustered B+ Tree index, **data entries are data records**

Hash-Based Index

Good for point queries but not range queries



Another example of unclustered/secondary index

Another example of clustered/primary index

Outline

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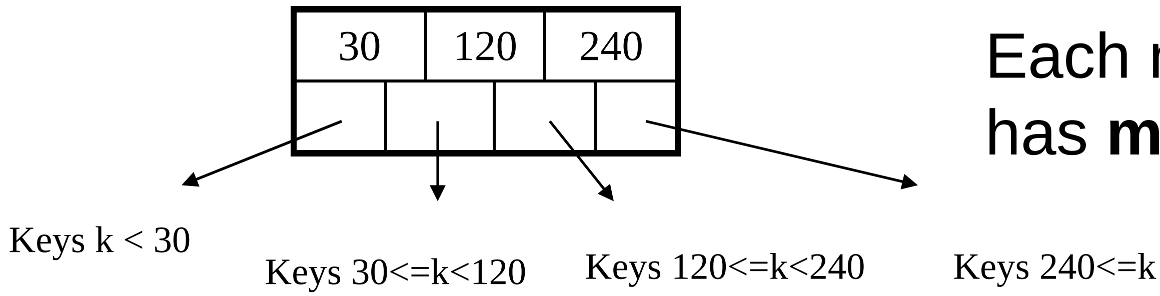
B+ Trees

- Search trees
- Idea in B Trees
  - Make 1 node = 1 block
  - Keep tree balanced in height
- Idea in B+ Trees
  - Make leaves into a linked list: facilitates range queries

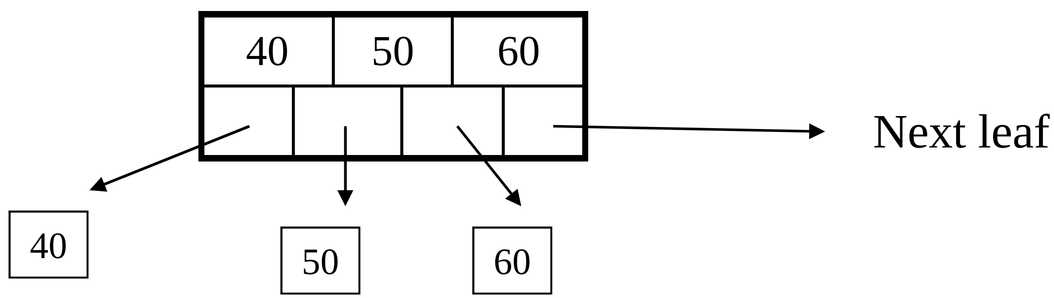
B+ Trees Basics

- Parameter d = the *degree*
- Each node has **d <= m <= 2d keys** (except root)



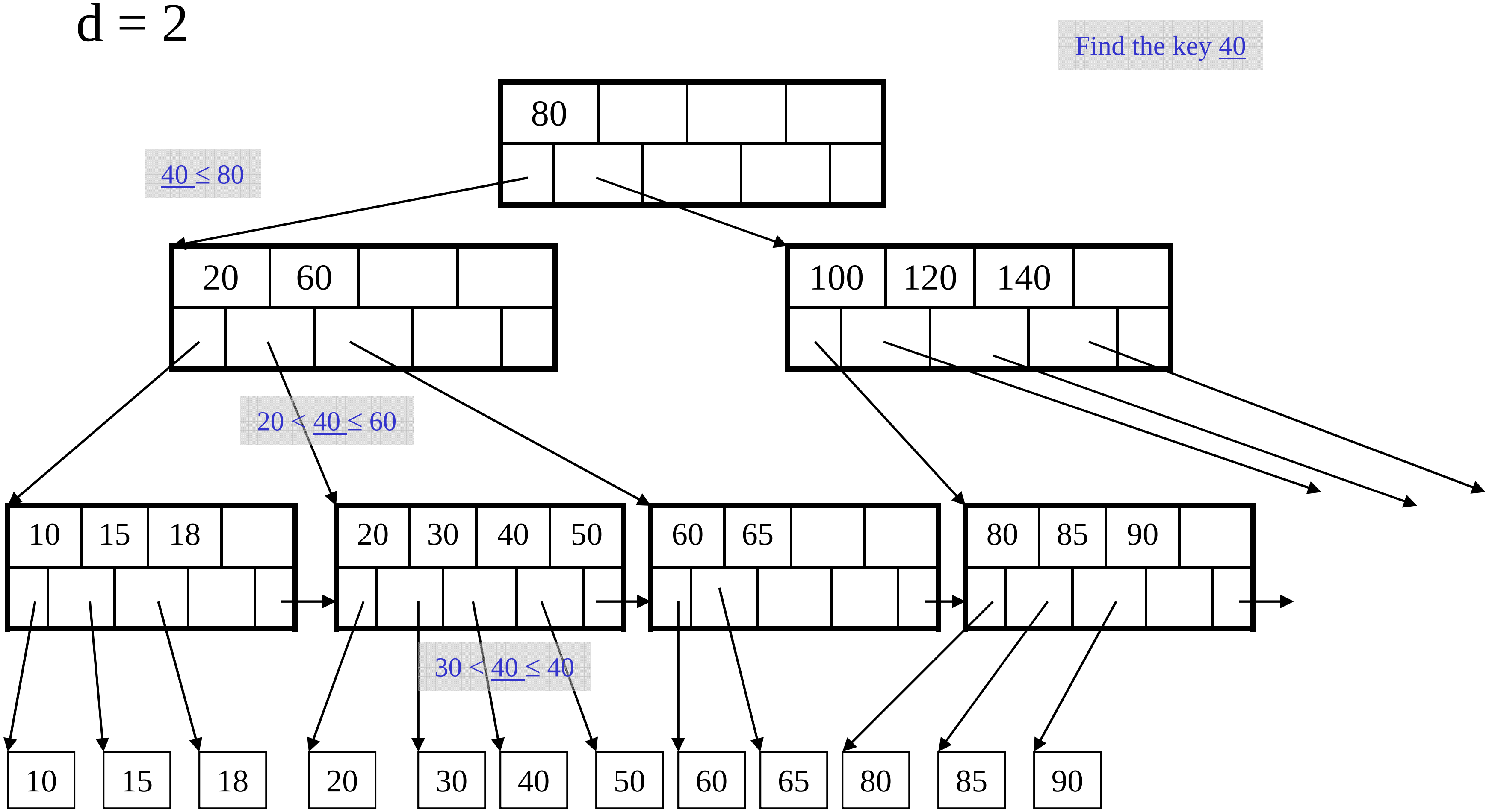
Each node also has **m+1 pointers**

- Each leaf has **d <= m <= 2d keys**



B+ Tree Example

d = 2



B+ Tree Design

- How large d ?
- Example:
  - Key size = 4 bytes
  - Pointer size = 8 bytes
  - Block size = 4096 bytes
- $2d \times 4 + (2d+1) \times 8 <= 4096$
- $d = 170$

Searching a B+ Tree

- Exact key values:
  - Start at the root
  - Proceed down, to the leaf

```
Select name
From people
Where age = 25
```

- Range queries:
  - As above
  - Then sequential traversal

```
Select name
From people
Where 20 <= age
  and  age <= 30
```

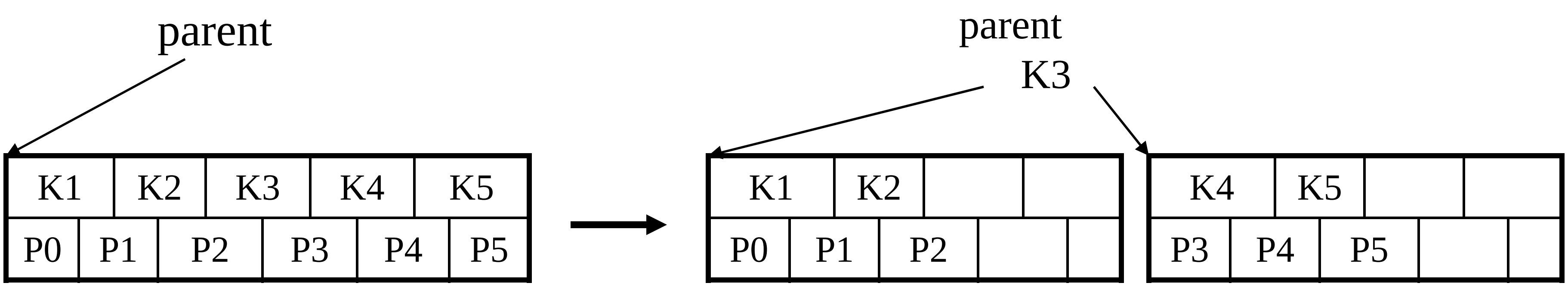
B+ Trees in Practice

- Typical order: 100. Typical fill-factor: 67%
  – average fanout = 133
- Typical capacities
  – Height 4: 133^4 = 312,900,700 records
  – Height 3: 133^3 = 2,352,637 records
- Can often hold top levels in buffer pool
  – Level 1 = 1 page = 8 Kbytes
  – Level 2 = 133 pages = 1 Mbyte
  – Level 3 = 17,689 pages = 133 Mbytes

Insertion in a B+ Tree

Insert (K, P)

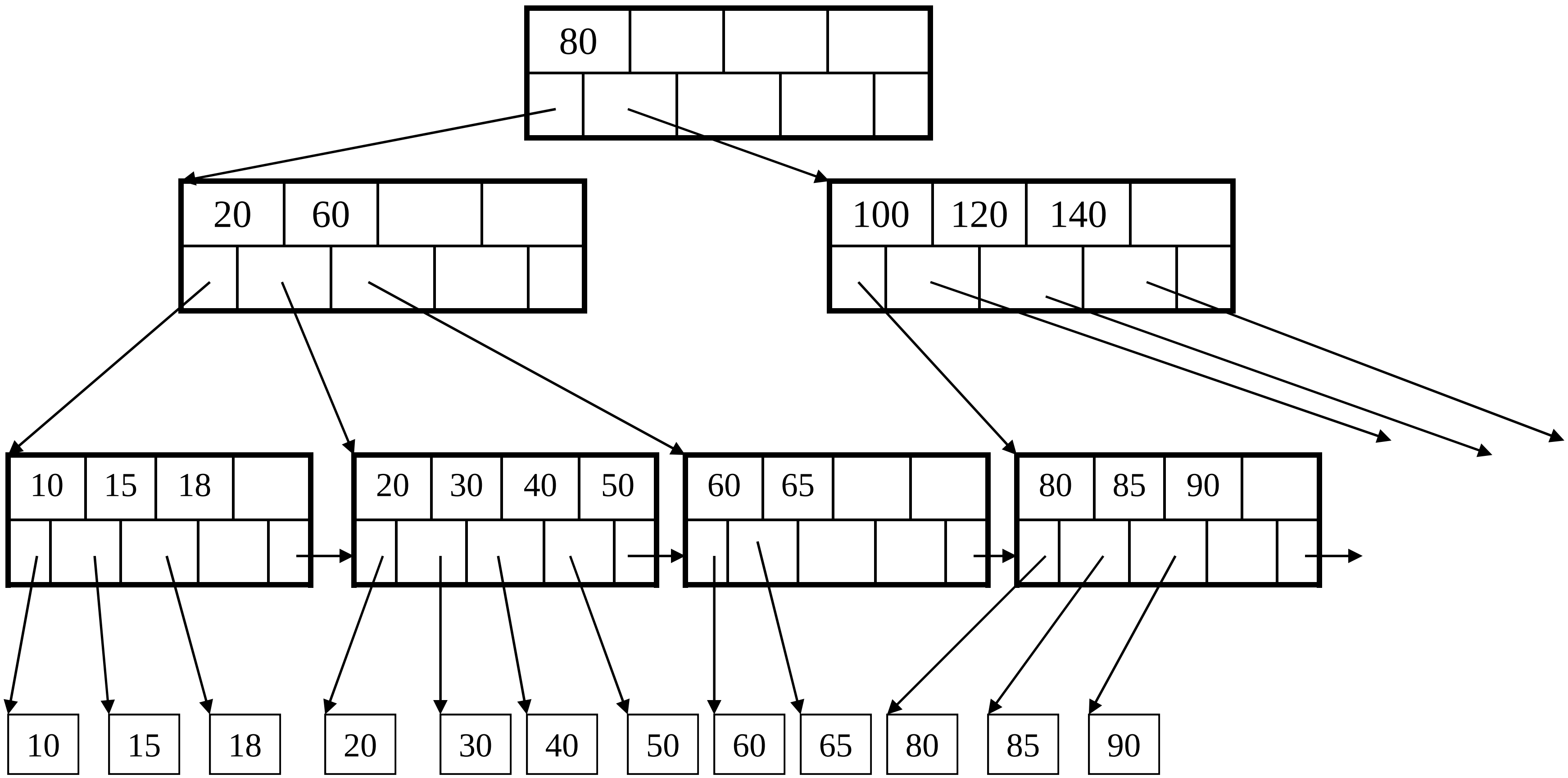
- Find leaf where K belongs, insert
- If no overflow (2d keys or less), halt
- If overflow (2d+1 keys), split node, insert in parent:



- If leaf, keep K3 too in right node
- When root splits, new root has 1 key only

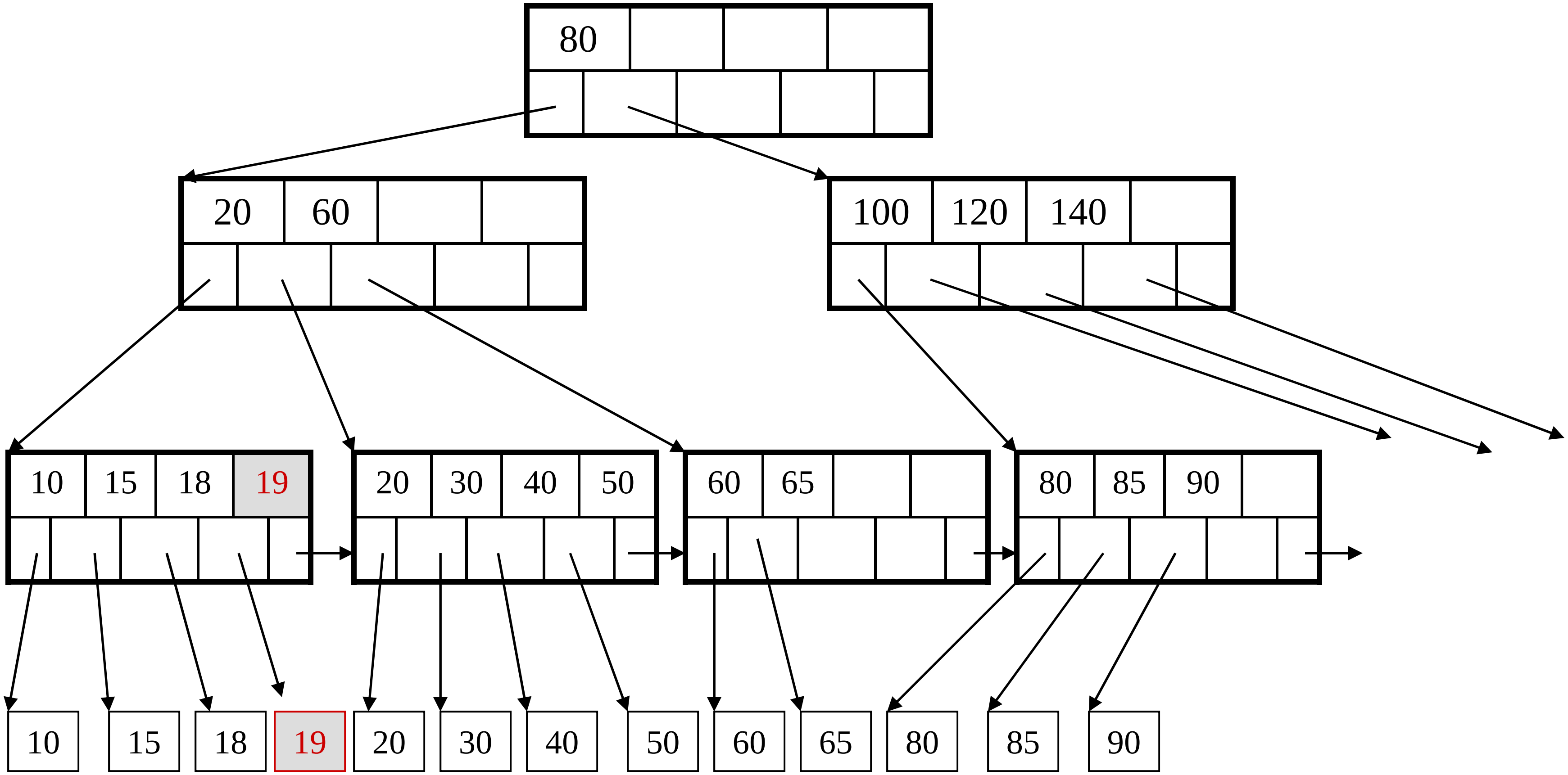
Insertion in a B+ Tree

Insert K=19



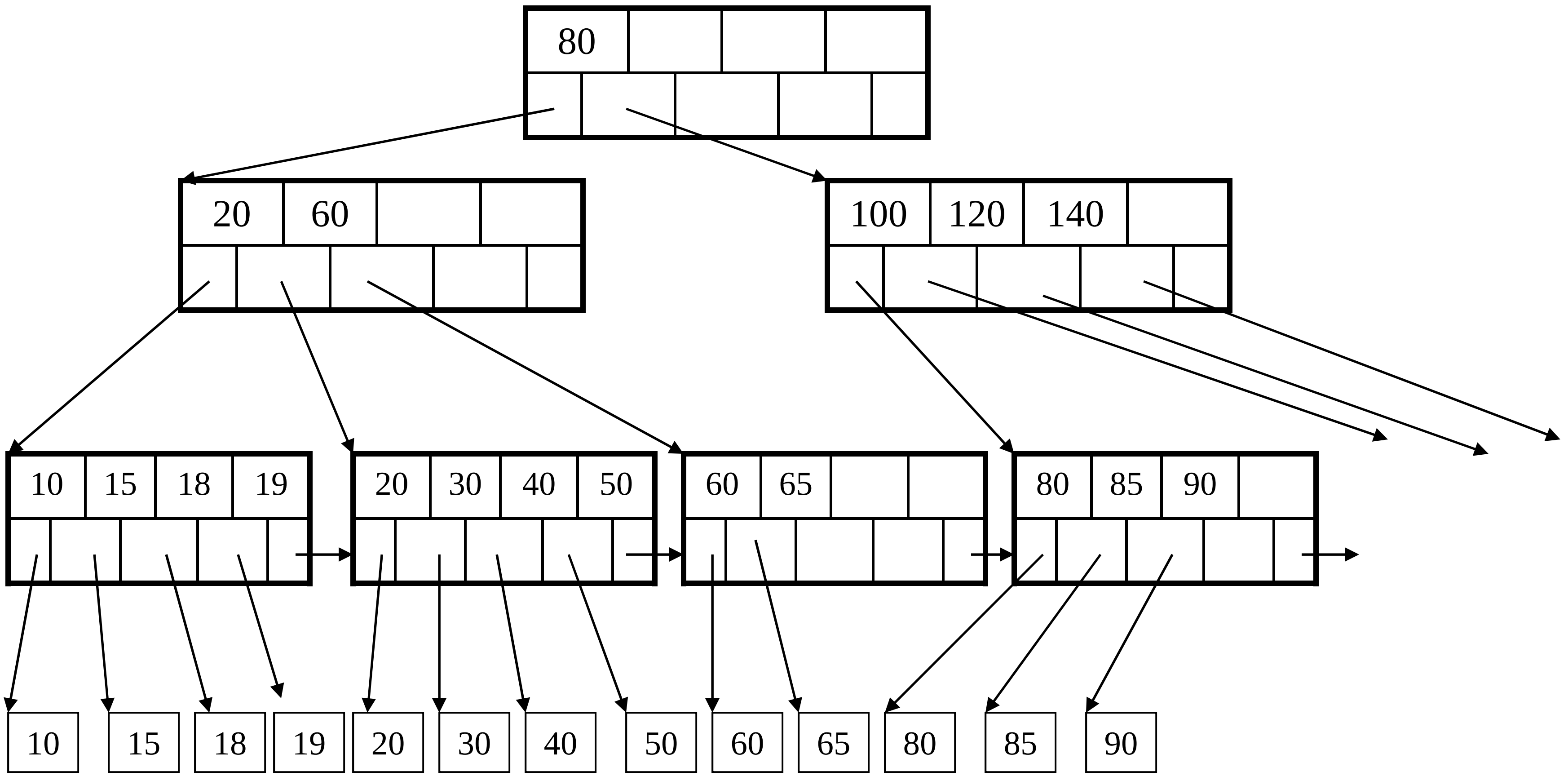
Insertion in a B+ Tree

After insertion



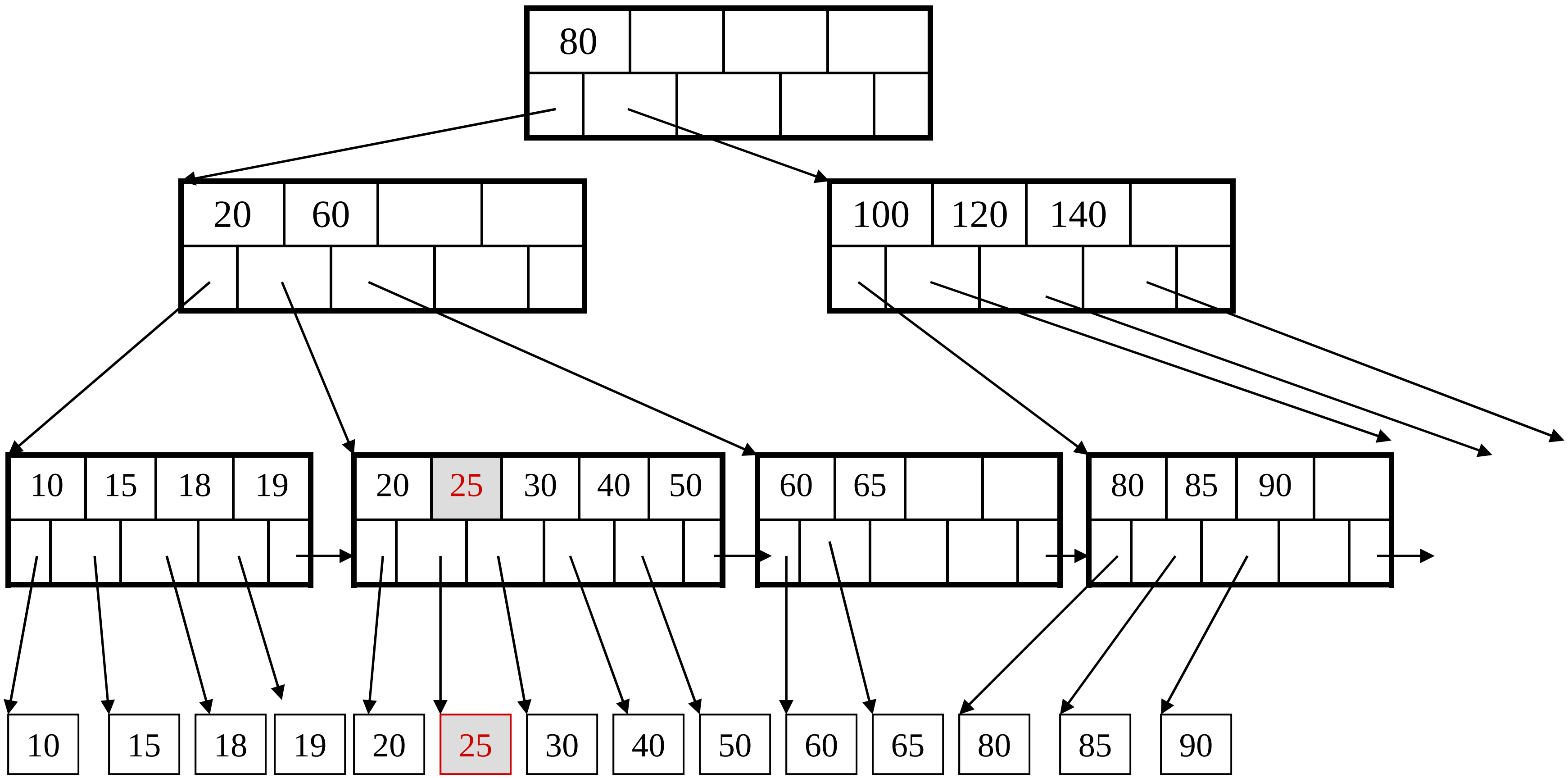
Insertion in a B+ Tree

Now insert 25



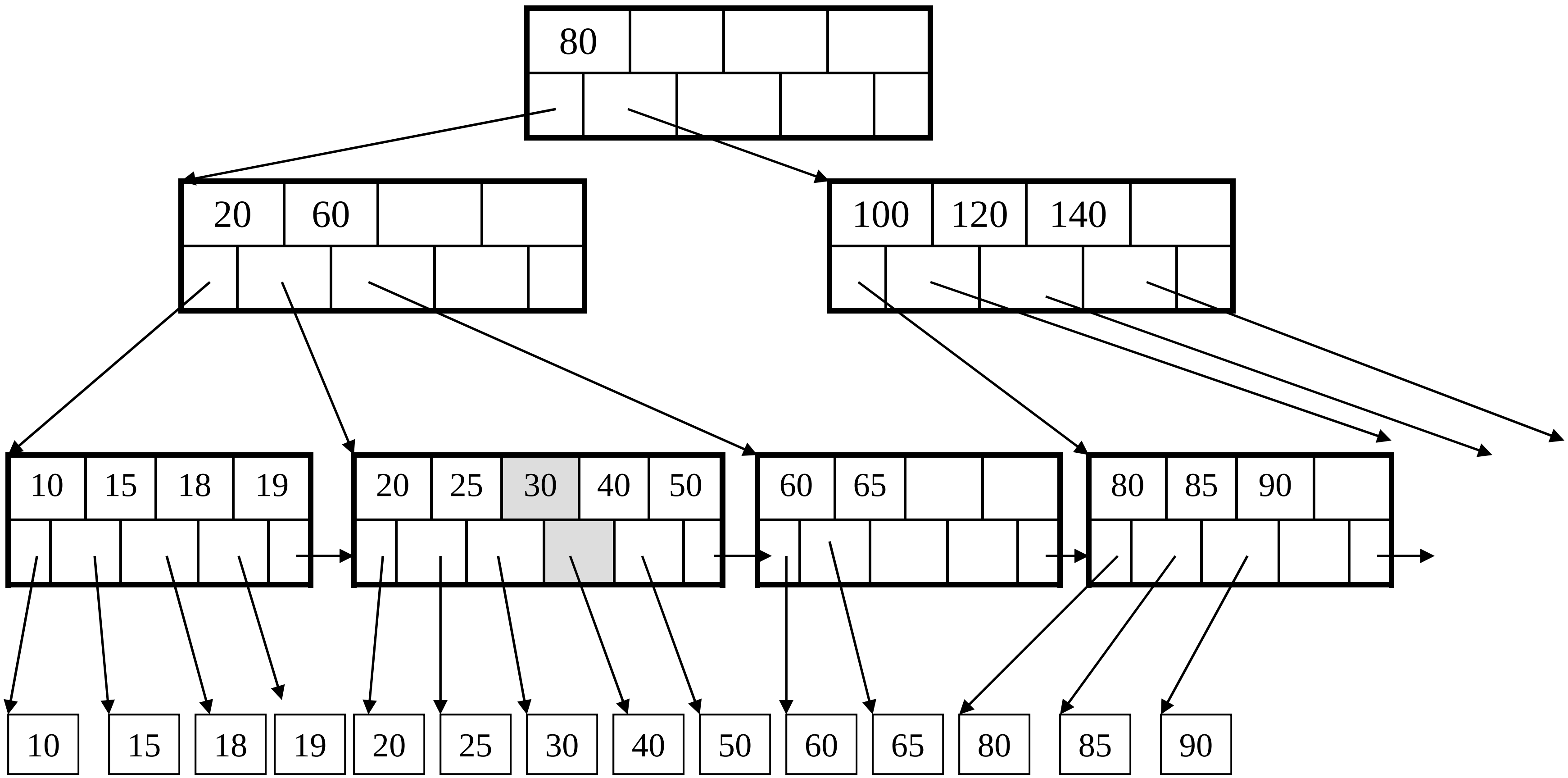
Insertion in a B+ Tree

After insertion



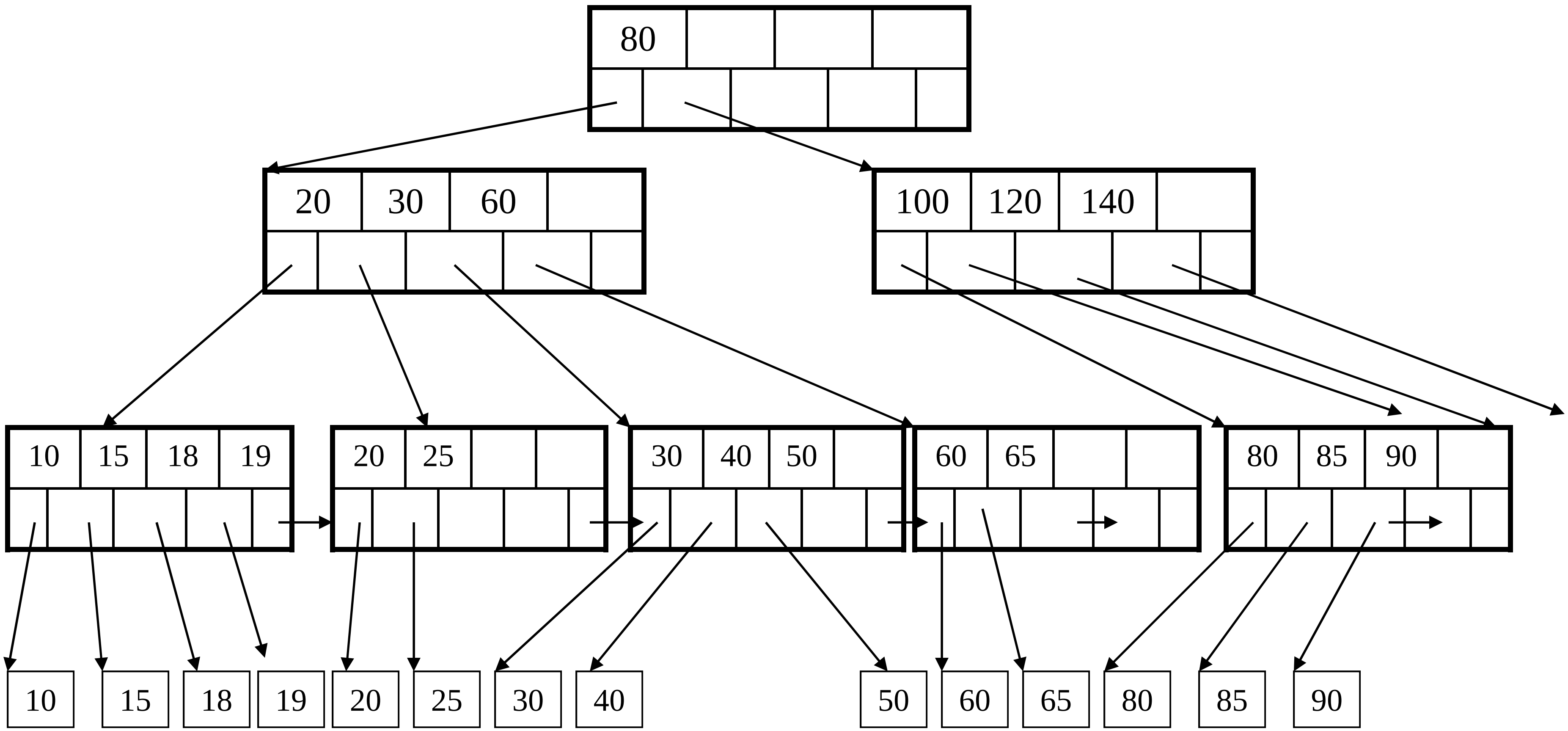
Insertion in a B+ Tree

But now have to split !



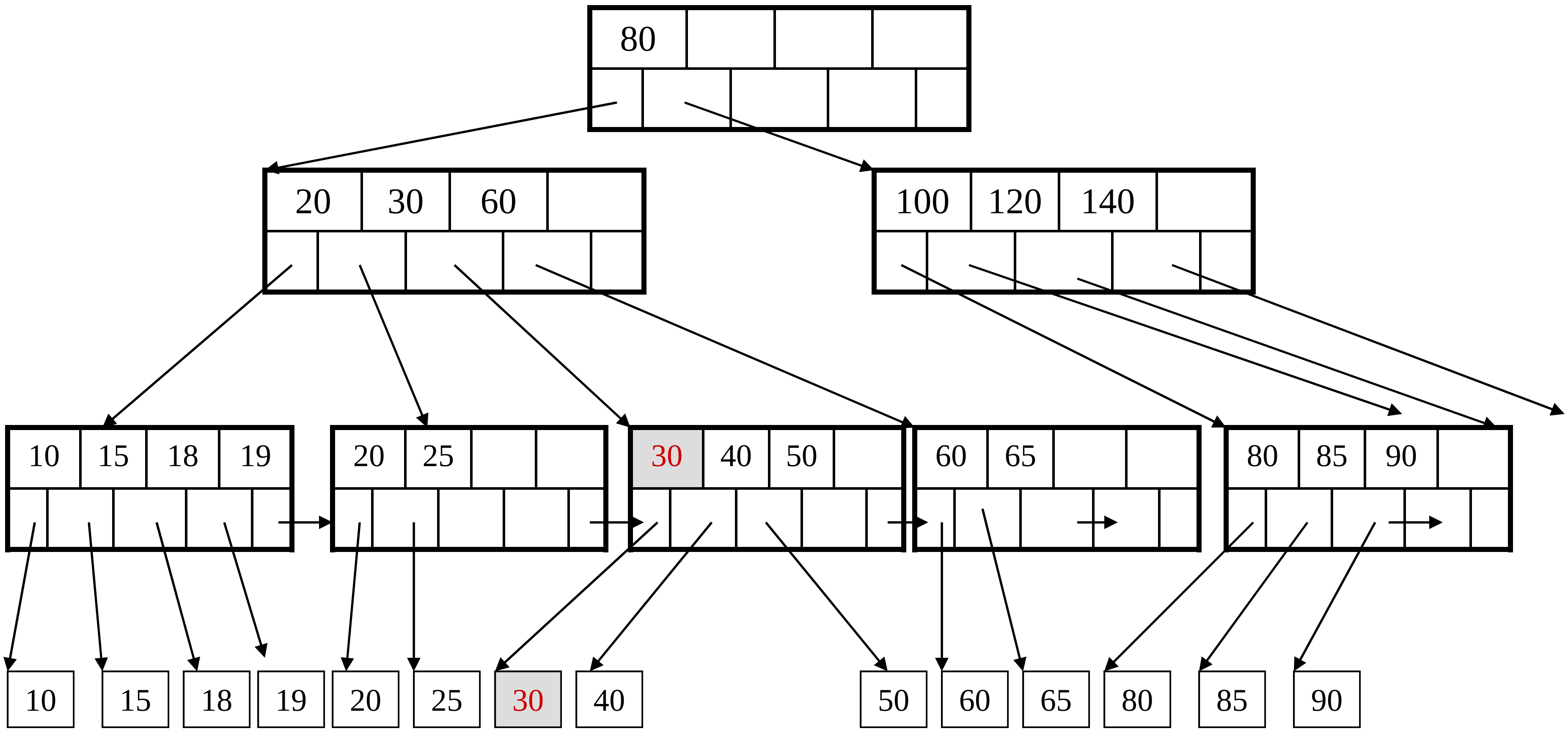
Insertion in a B+ Tree

After the split



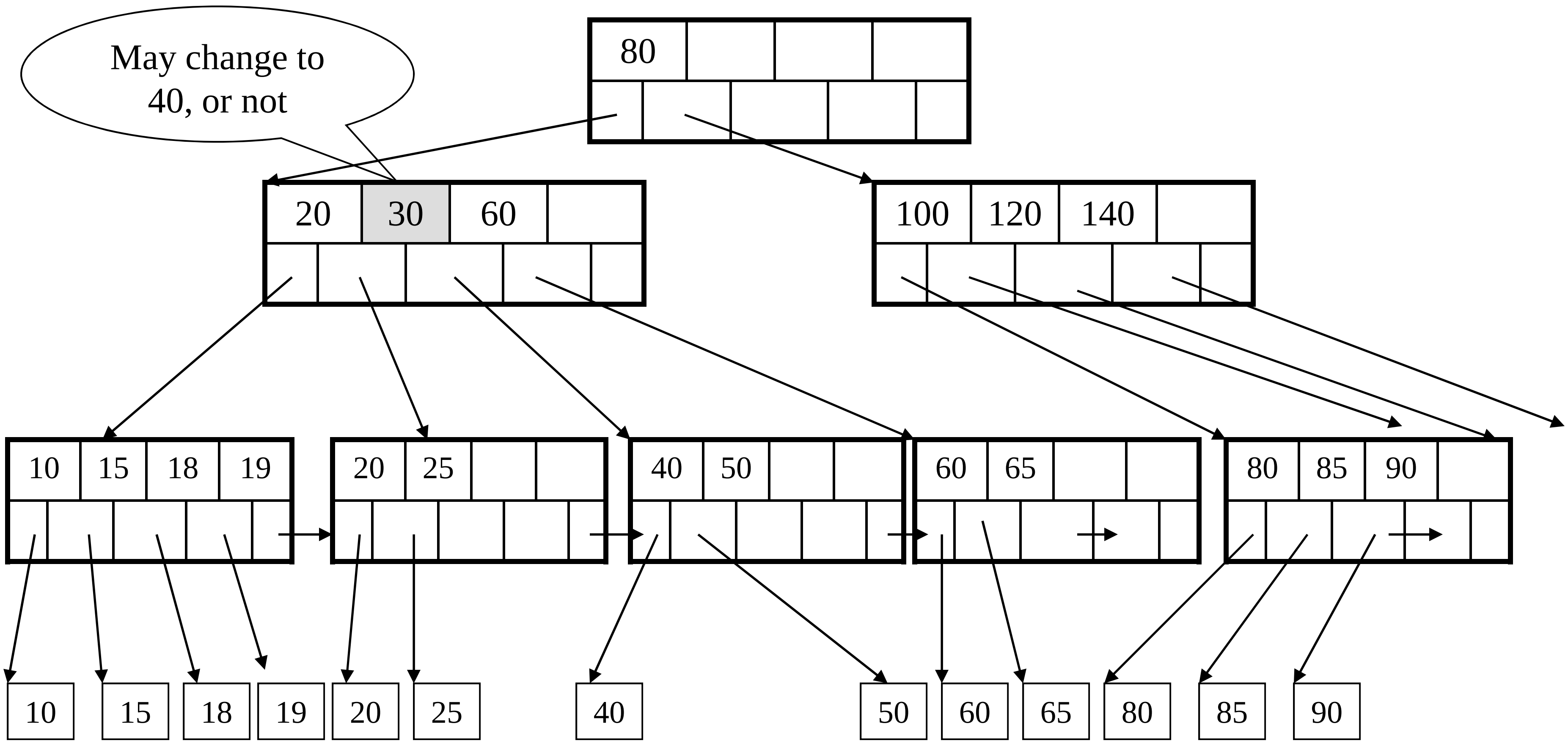
Deletion from a B+ Tree

Delete 30



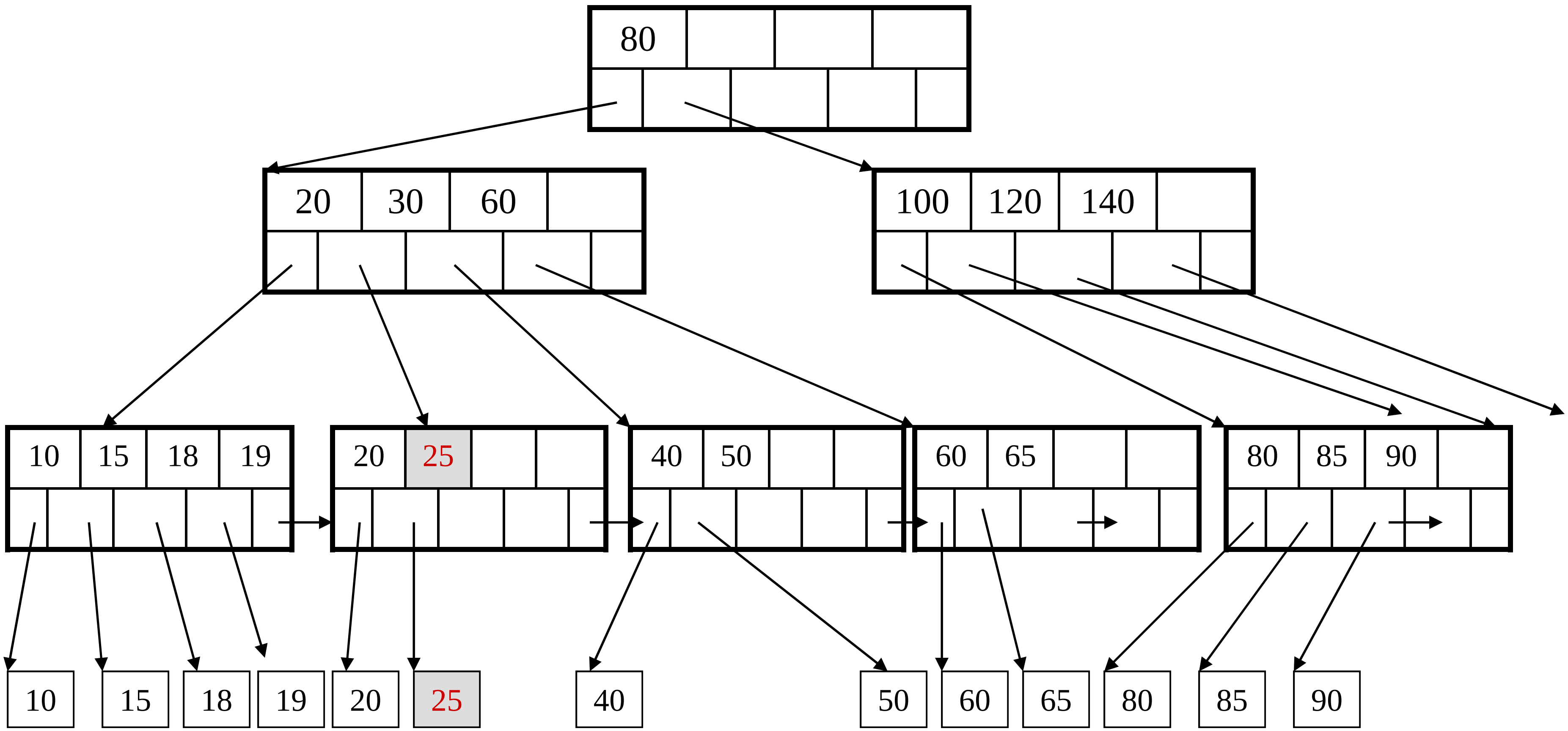
Deletion from a B+ Tree

After deleting 30



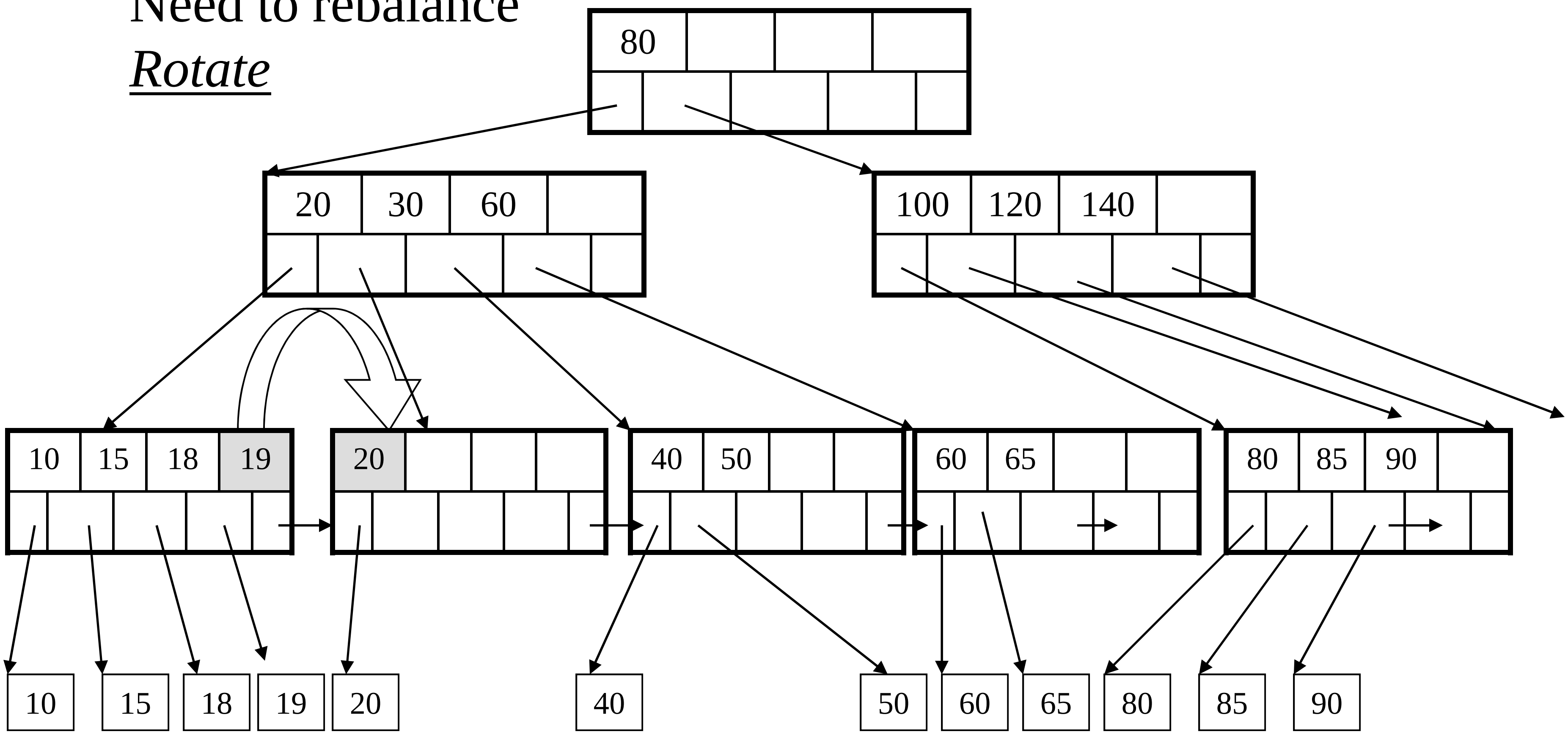
Deletion from a B+ Tree

Now delete 25



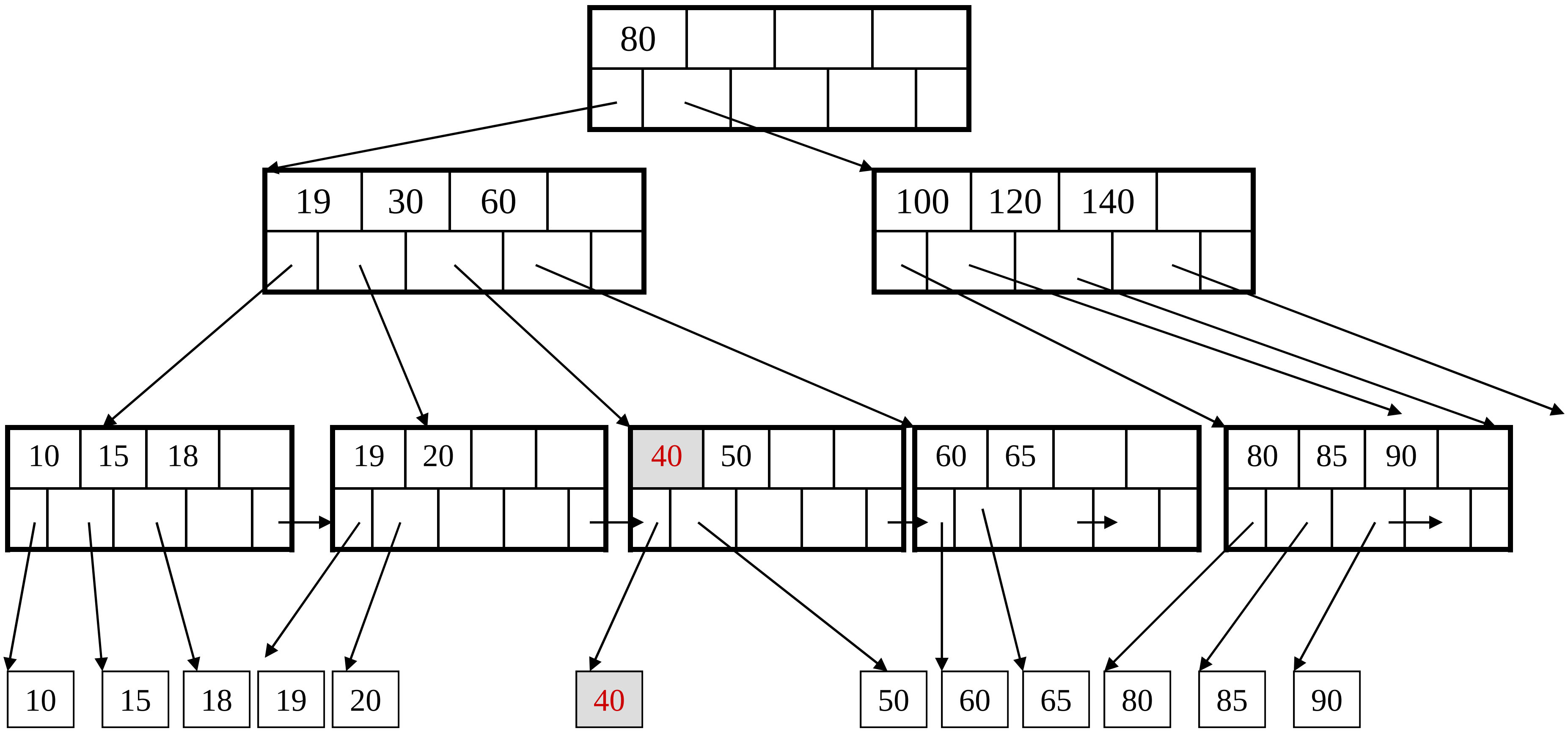
Deletion from a B+ Tree

After deleting 25
Need to rebalance
Rotate



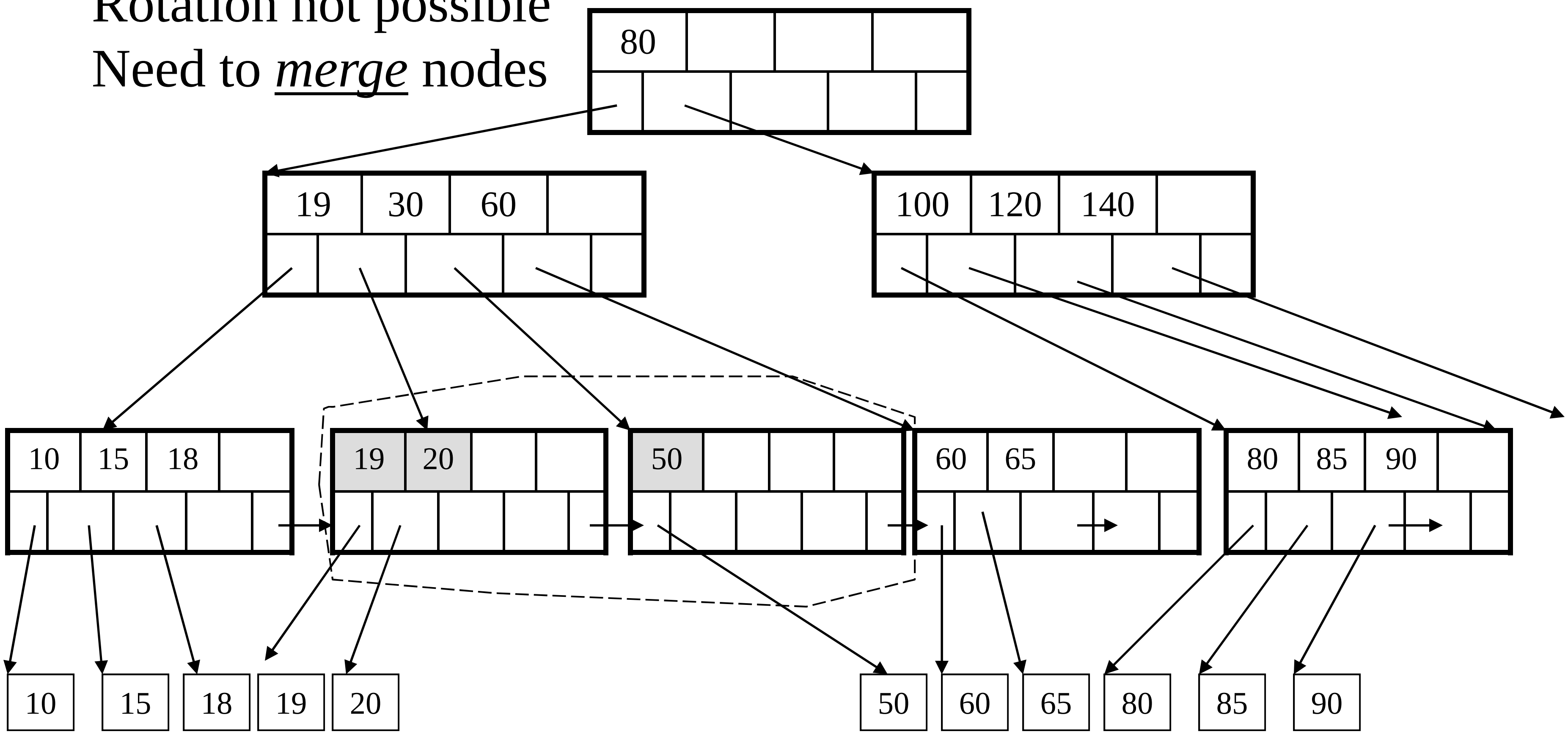
Deletion from a B+ Tree

Now delete 40



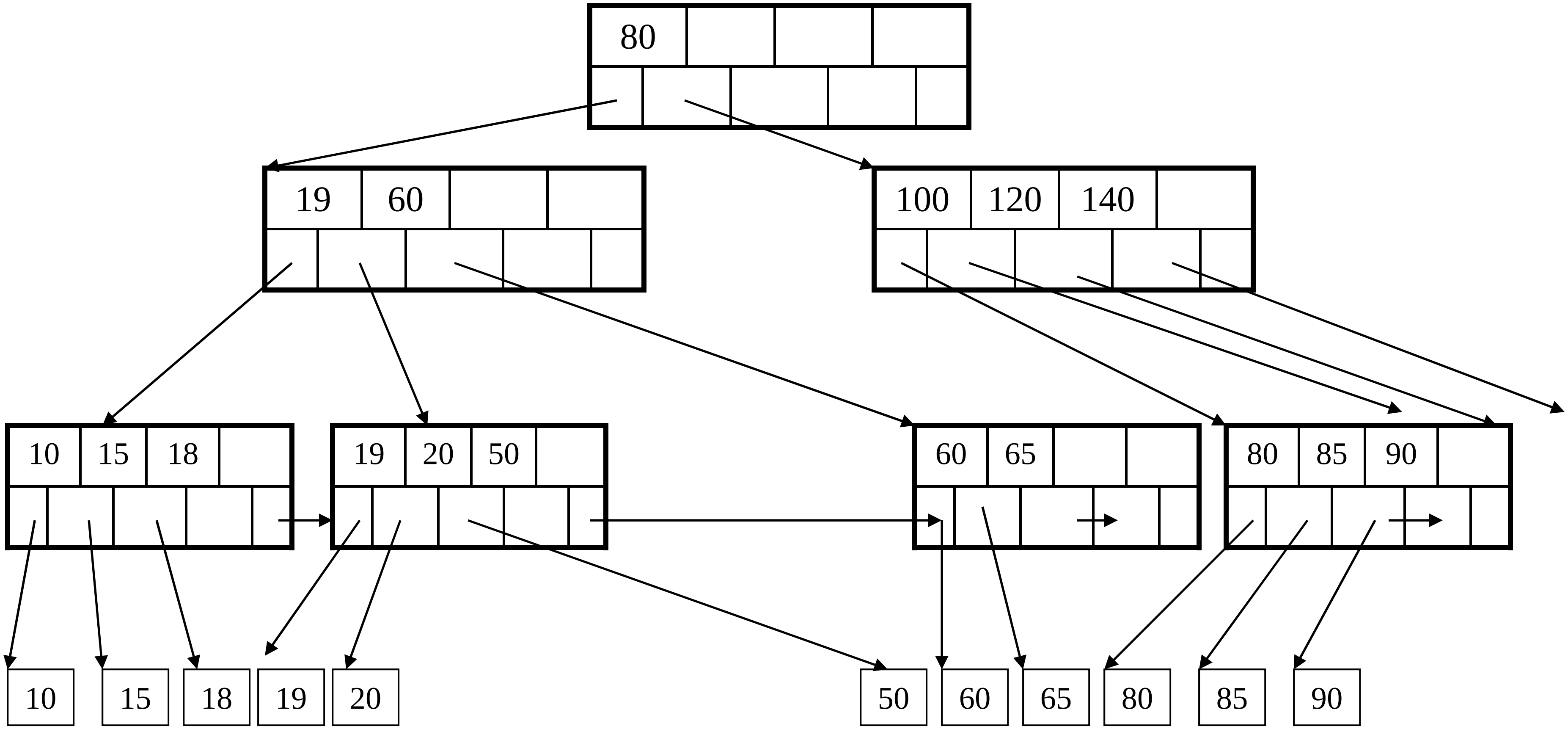
Deletion from a B+ Tree

After deleting 40
Rotation not possible
Need to *merge* nodes



Deletion from a B+ Tree

Final tree



Summary of B+ Trees

- Default index structure on most DBMS
- Very effective at answering ‘point’ queries:
  productName = ‘gizmo’
- Effective for range queries:
  50 < price AND price < 100
- Less effective for multirange:
  50 < price < 100 AND 2 < quant < 20

Indexes in PostgreSQL

```
CREATE  TABLE    V(M int,   N varchar(20),    P int);
```

```
CREATE  INDEX V1_N ON V(N)
```

```
CREATE  INDEX V2 ON V(P, M)
```

```
CREATE  INDEX VVV ON V(M, N)
```

```
CLUSTER V USING V2
```

Makes V2 clustered