CSE 444: Database Internals

Lectures 5-6

Indexing

Announcements

- HW1 due tonight by 11pm
  - Turn in an electronic copy (word/pdf) by 11pm, or
  - Turn in a hard copy after class

- Lab1 is due Friday, 11pm
  - Do not fall behind on the labs! They build on each other

Basic Access Method: Heap File

API

- **Create** or **destroy** a file
- **Insert** a record
- **Delete** a record with a given rid (rid)
  - rid: unique tuple identifier (more later)
- **Get** a record with a given rid
  - Not necessary for sequential scan operator
  - But used with indexes
- **Scan** all records in the file

But Often Also Want….

- **Scan** all records in the file that match a **predicate** of the form **attribute op value**
  - Example: Find all students with GPA > 3.5

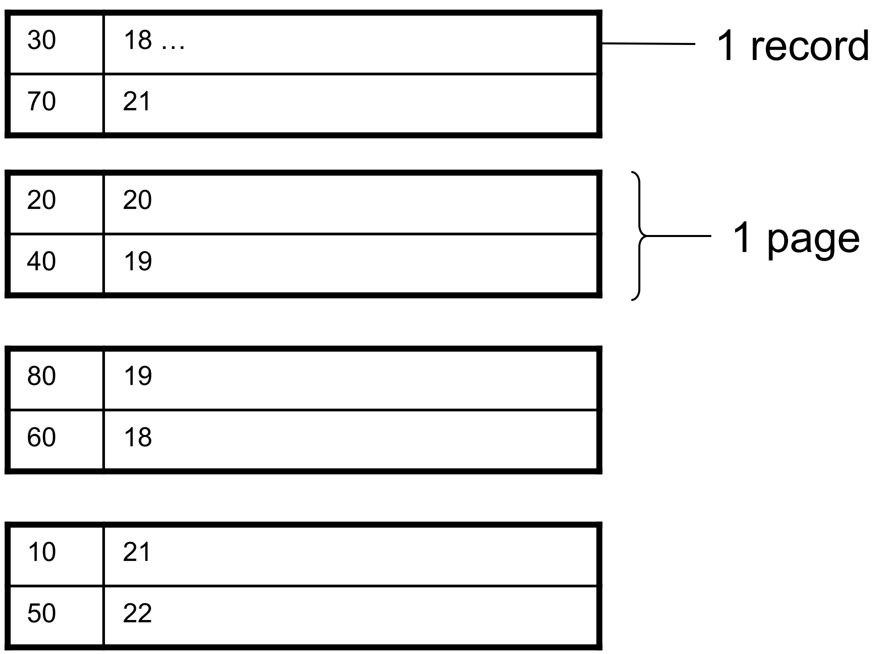
- Critical to support such requests efficiently
  - Why read all data form disk when we only need a small fraction of that data?

- This lecture and next, we will learn how

Searching in a Heap File

File is not sorted on any attribute

`Student(sid: int, age: int, …)`



Heap File Search Example

- 10,000 students
- 10 student records per page
- Total number of pages: 1,000 pages
- Find student whose sid is 80
  - Must read on average 500 pages
- Find all students older than 20
  - Must read all 1,000 pages
- Can we do better?

Sequential File

File sorted on an attribute, usually on primary key

`Student(sid: int, age: int, …)`

10	21 …
20	20

30	18
40	19

50	22
60	18

70	21
80	19

Sequential File Example

- Total number of pages: 1,000 pages
- Find student whose sid is 80
  - Could do binary search, read $\log_2(1{,}000) \approx 10$ pages
- Find all students older than 20
  - Must still read all 1,000 pages
- Can we do even better?

- Note: Sorted files are inefficient for inserts/deletes

Outline

- Index structures
- Hash-based indexes
- B+ trees

} Today

} Next time

Indexes

- **Index:** data structure that organizes data records on disk to optimize selections on the ***search key fields*** for the index
- An index contains a collection of ***data entries***, and supports efficient retrieval of all data entries with a given search key value **k**
- Indexes are also access methods!
  - So they provide the same API as we have seen for Heap Files
  - And efficiently support scans over tuples matching a predicate on the search key

Indexes

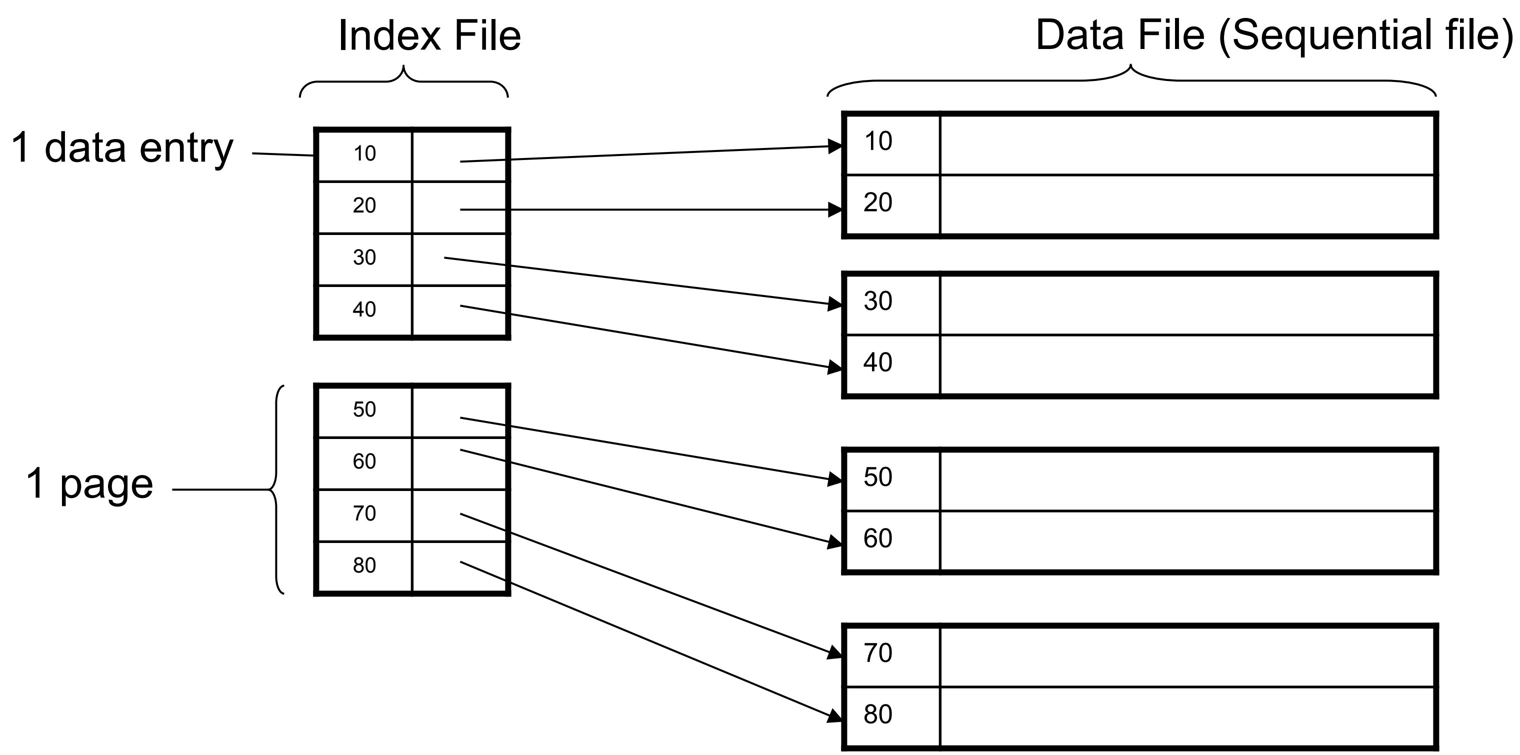
- **Search key** = can be any set of fields
  - not the same as the primary key, nor a key
- **Index** = collection of data entries
- **Data entry** for key k can be:
  - The actual record with key k
    - In this case, **the index is also a special file organization**
    - Called: “indexed file organization”
  - (k, RID)
  - (k, list-of-RIDs)

Different Types of Files

- For the data inside base relations:
  - Heap file (tuples stored without any order)
  - Sequential file (tuples sorted some attribute(s))
  - Indexed file (tuples organized following an index)
- Then we can have additional index files that store (key,rid) pairs
- Index can also be a "covering index"
  - Index contains (search key + other attributes, rid)
  - Index suffices to answer some queries

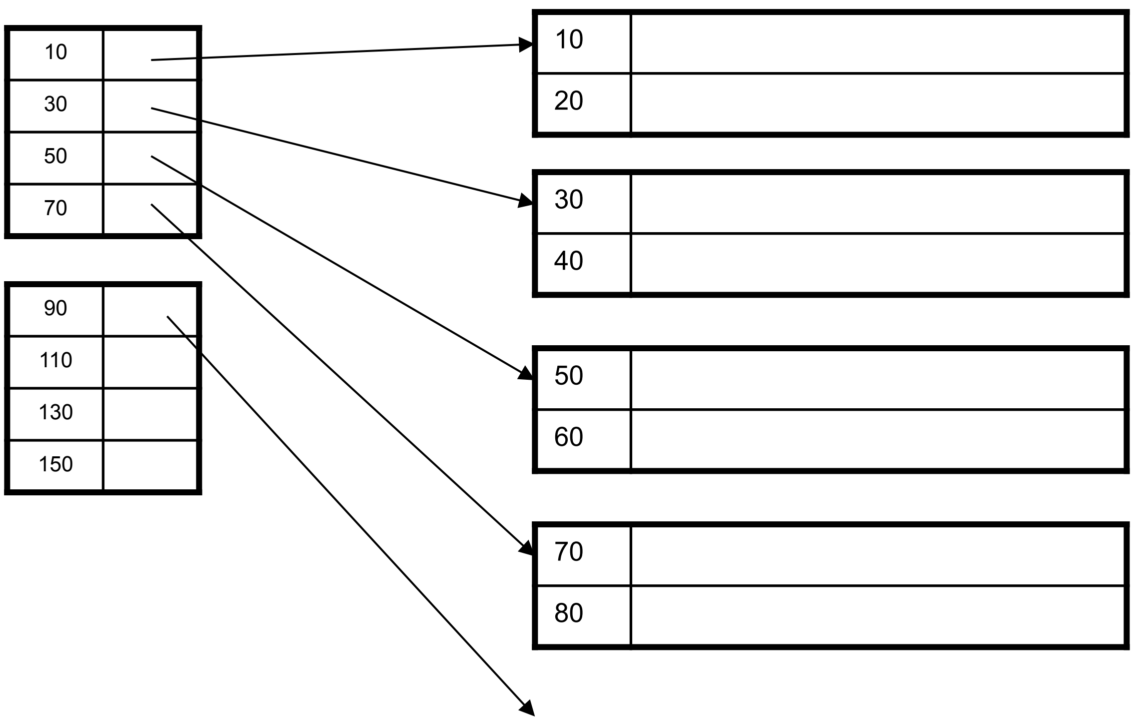
Primary Index

- Primary index determines location of indexed records
- *Dense* index: sequence of (key,rid) pairs



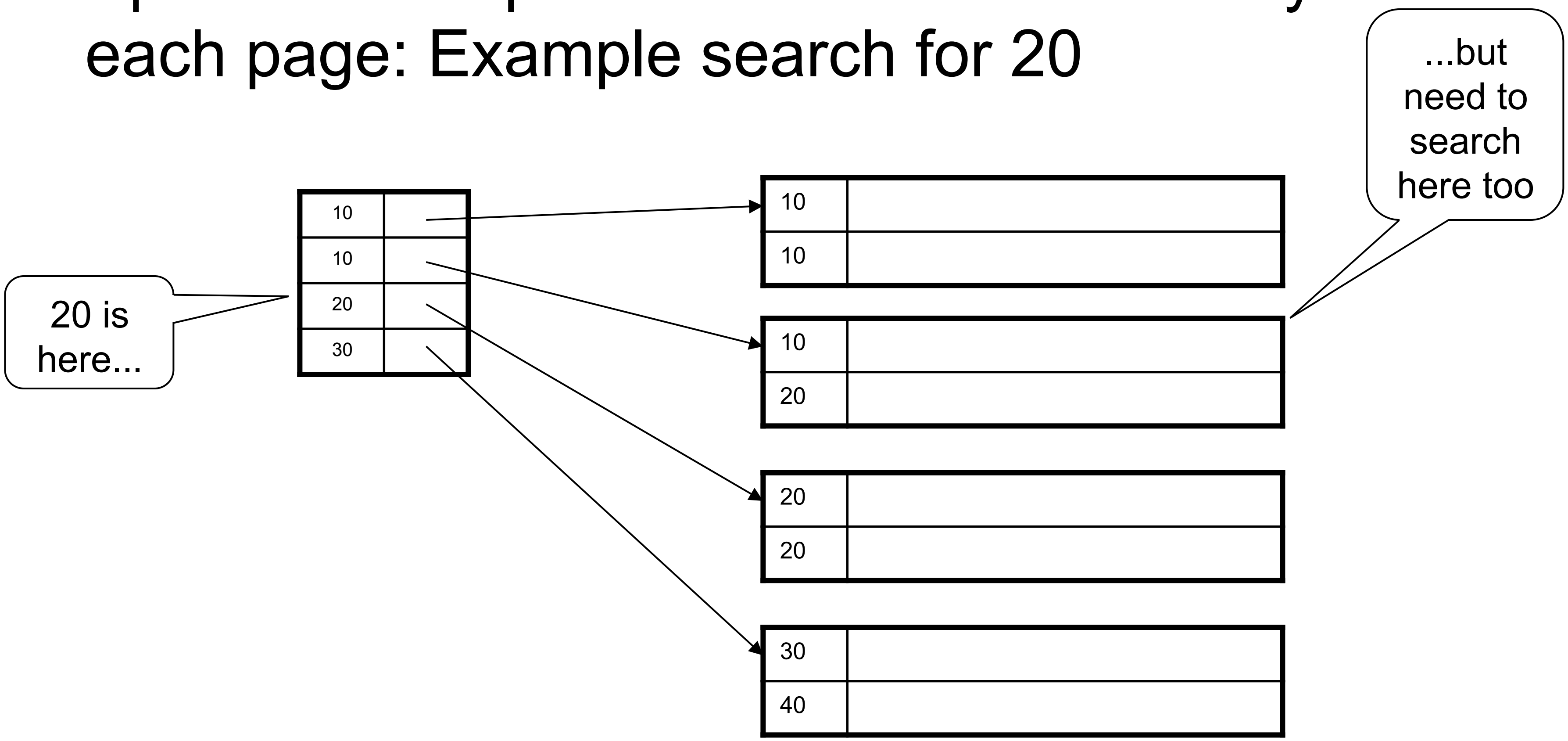
Primary Index

- *Sparse* index



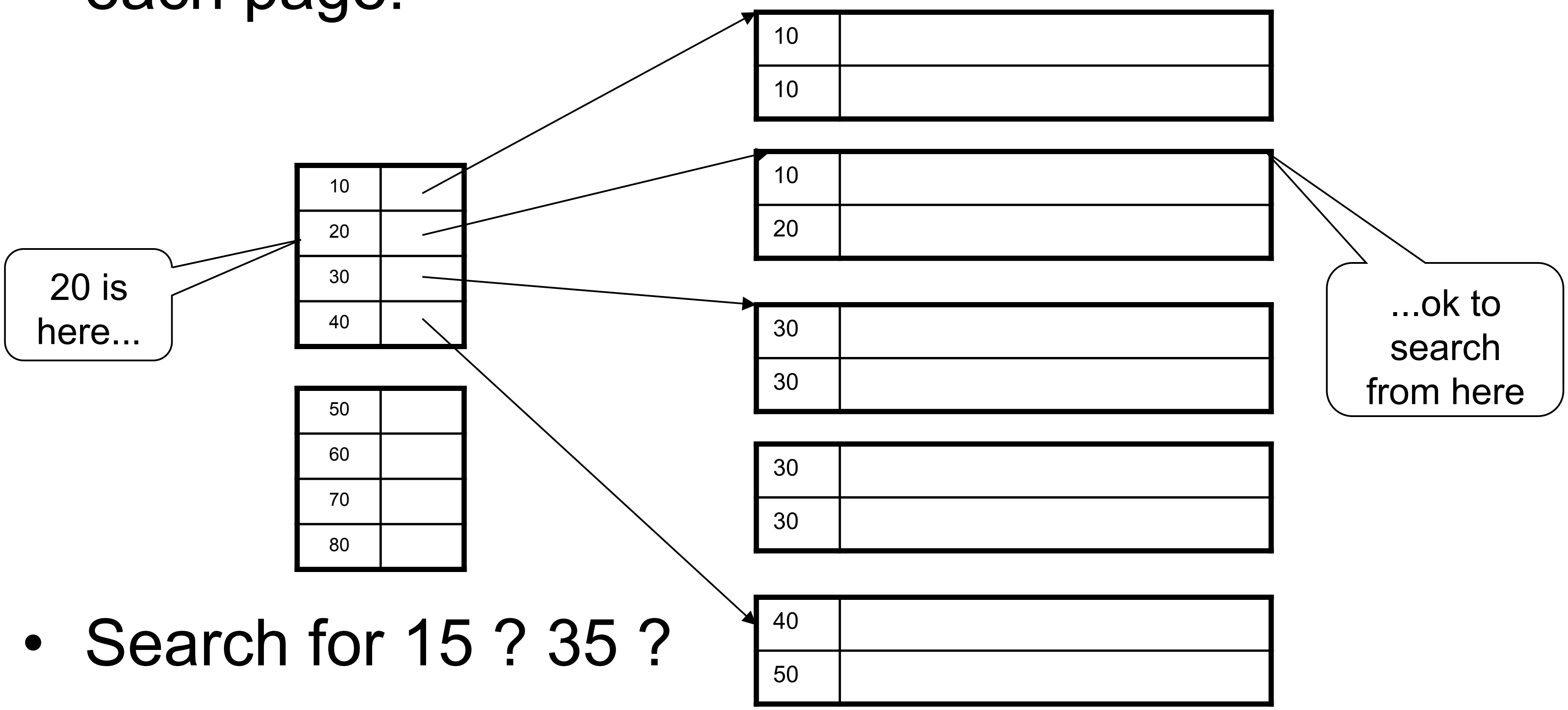
Primary Index with Duplicate Keys

- Sparse index: pointer to lowest search key on each page: Example search for 20



Primary Index with Duplicate Keys

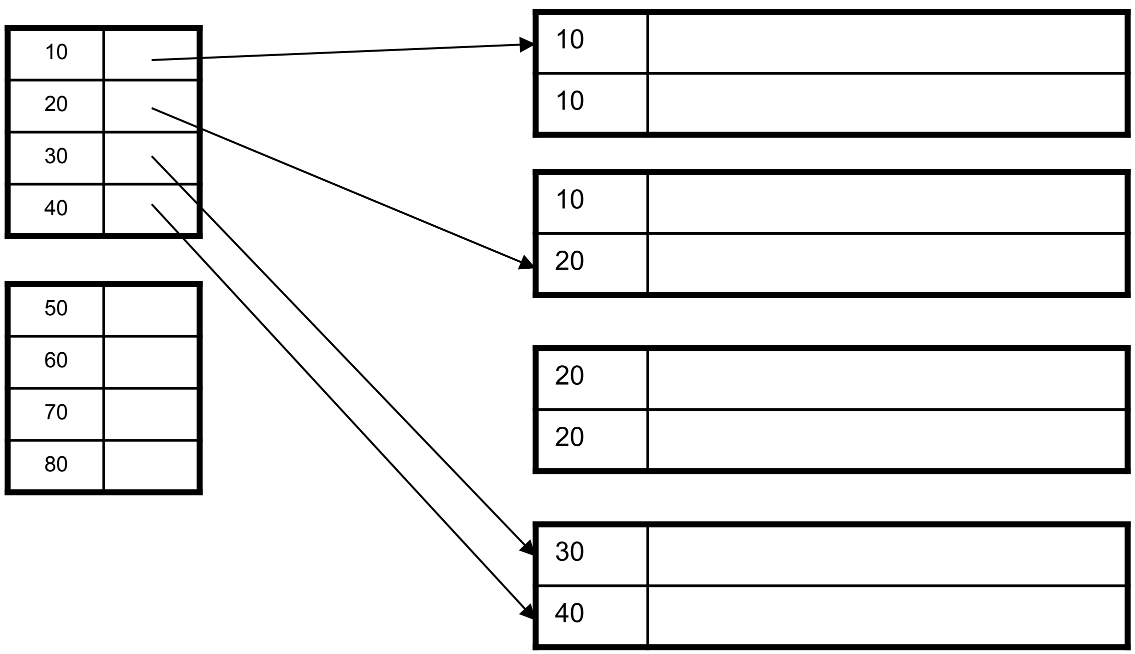
- Better: pointer to ***lowest new search key*** on each page:



- Search for 15 ? 35 ?

Primary Index with Duplicate Keys

- Dense index:



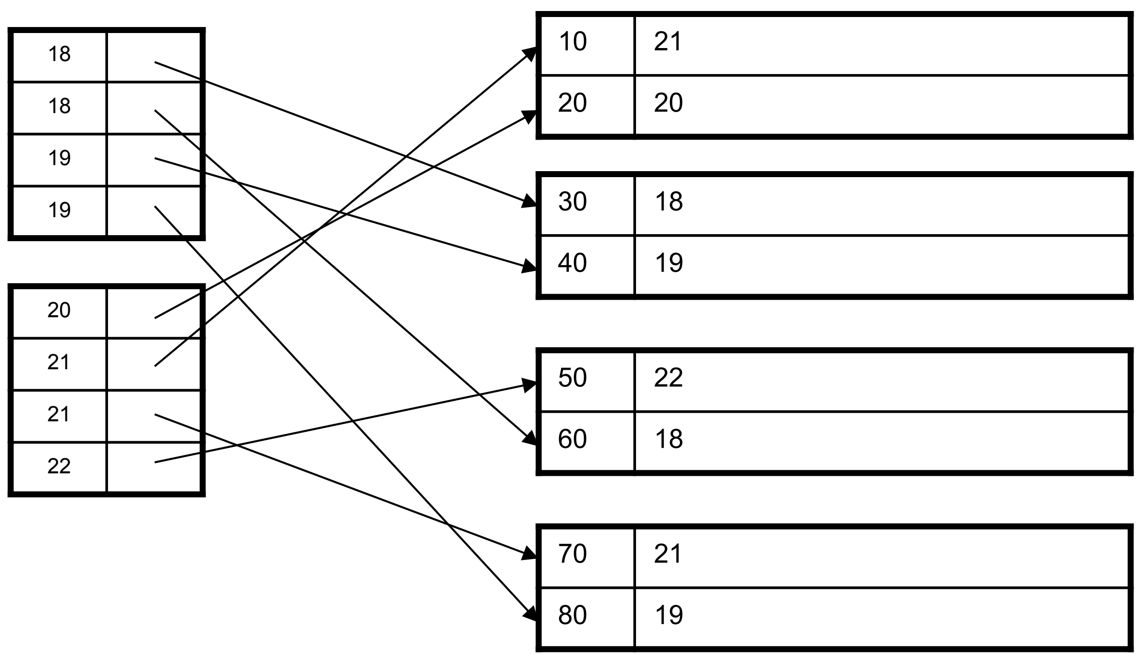
Primary Index: Back to Example

- Let's assume all pages of index fit in memory

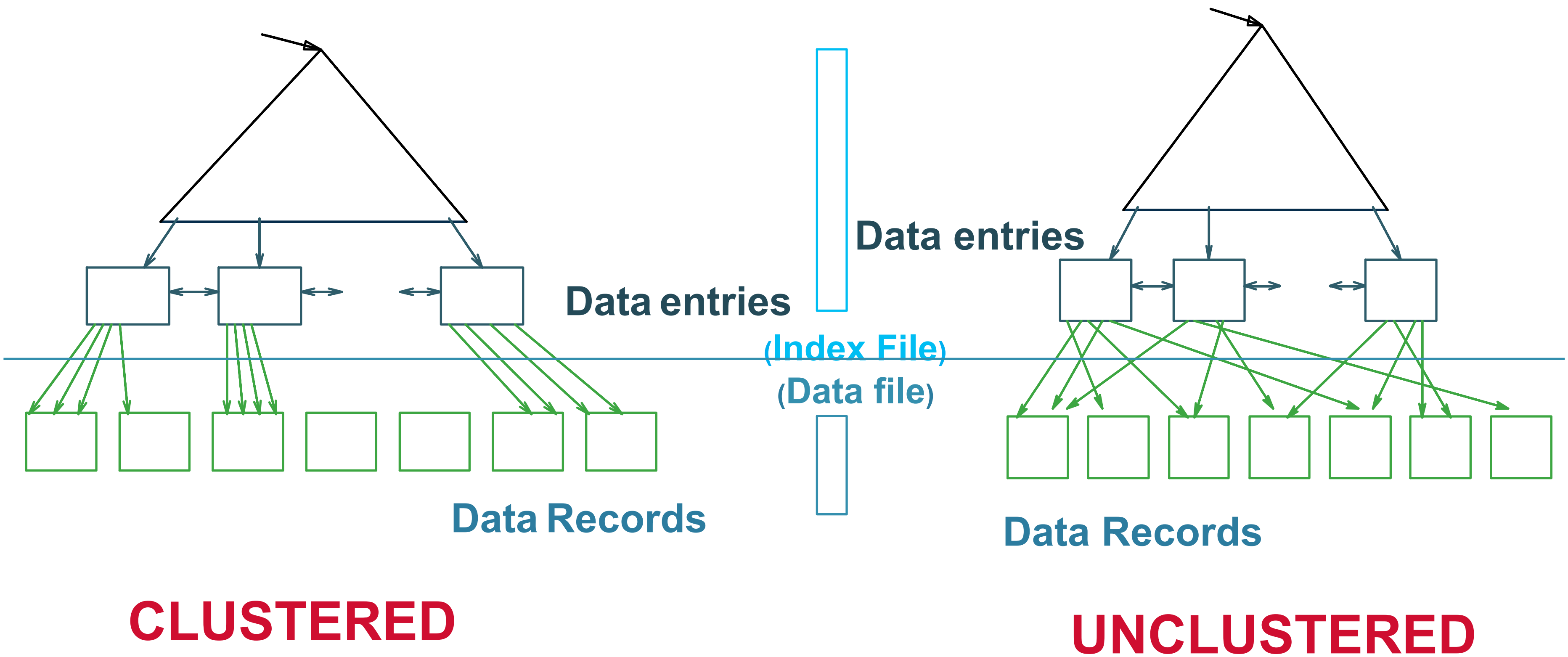
- Find student whose sid is 80
  - Index (dense or sparse) points directly to the page
  - Only need to read 1 page from disk.
- Find all students older than 20
  - Must still read all 1,000 pages.
- How can we make *both* queries fast?

Secondary Indexes

- To index other attributes than primary key
- Always dense (why ?)



Clustered vs. Unclustered Index



Clustered = records close in index are close in data

Clustered/Unclustered

- Primary index = clustered by definition
- Secondary indexes = usually unclustered

Secondary Indexes

- Applications
  - Index other attributes than primary key
  - Index unsorted files (heap files)
  - Index files that hold data from two relations
    - Called “clustered file”
    - Notice the different use of the term “clustered”!

Index Classification Summary

- Primary/secondary
  - Primary = determines the location of indexed records
  - Secondary = cannot reorder data, does not determine data location
- Dense/sparse
  - Dense = every key in the data appears in the index
  - Sparse = the index contains only some keys
- Clustered/unclustered
  - Clustered = records close in index are close in data
  - Unclustered = records close in index may be far in data
- B+ tree / Hash table / …

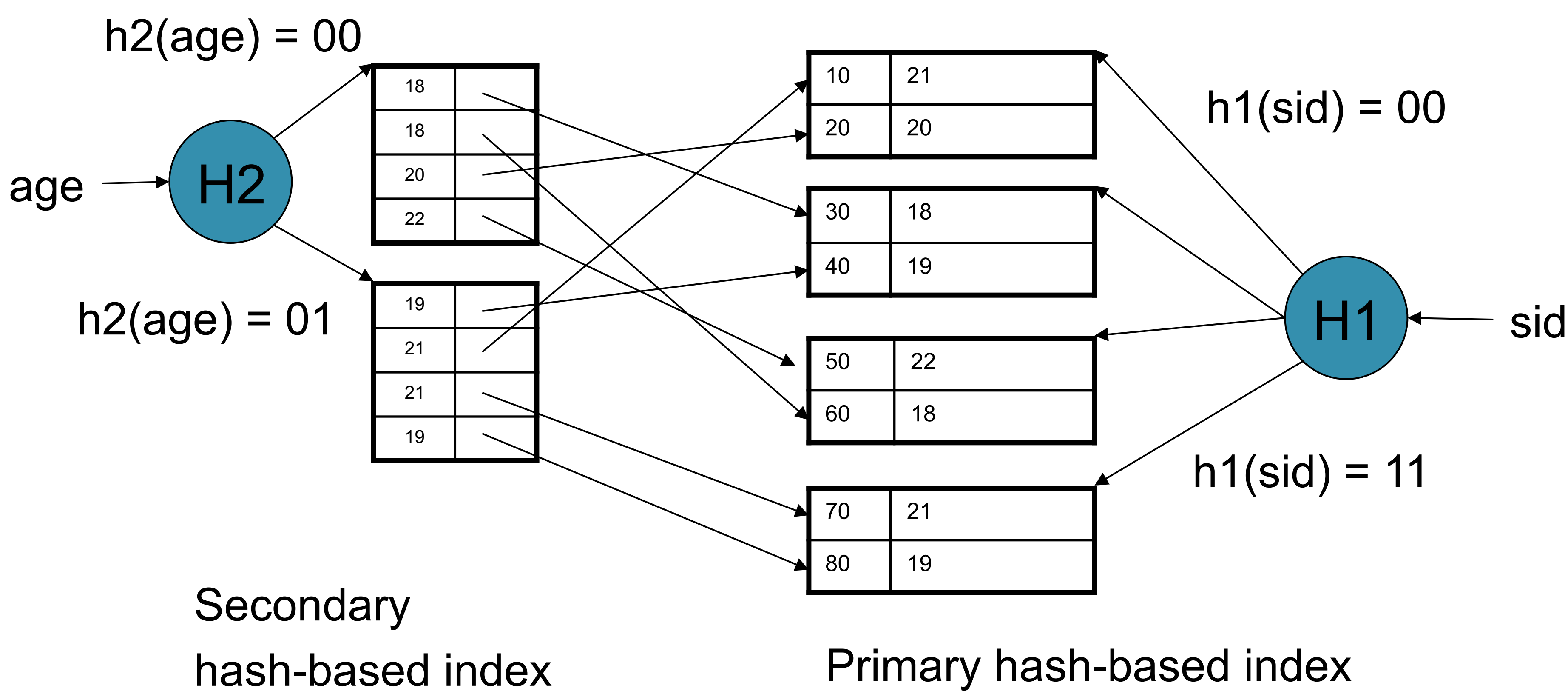
Large Indexes

- What if index does not fit in memory?

- Would like to index the index itself
  - Hash-based index
  - Tree-based index

Hash-Based Index

Good for point queries but not range queries



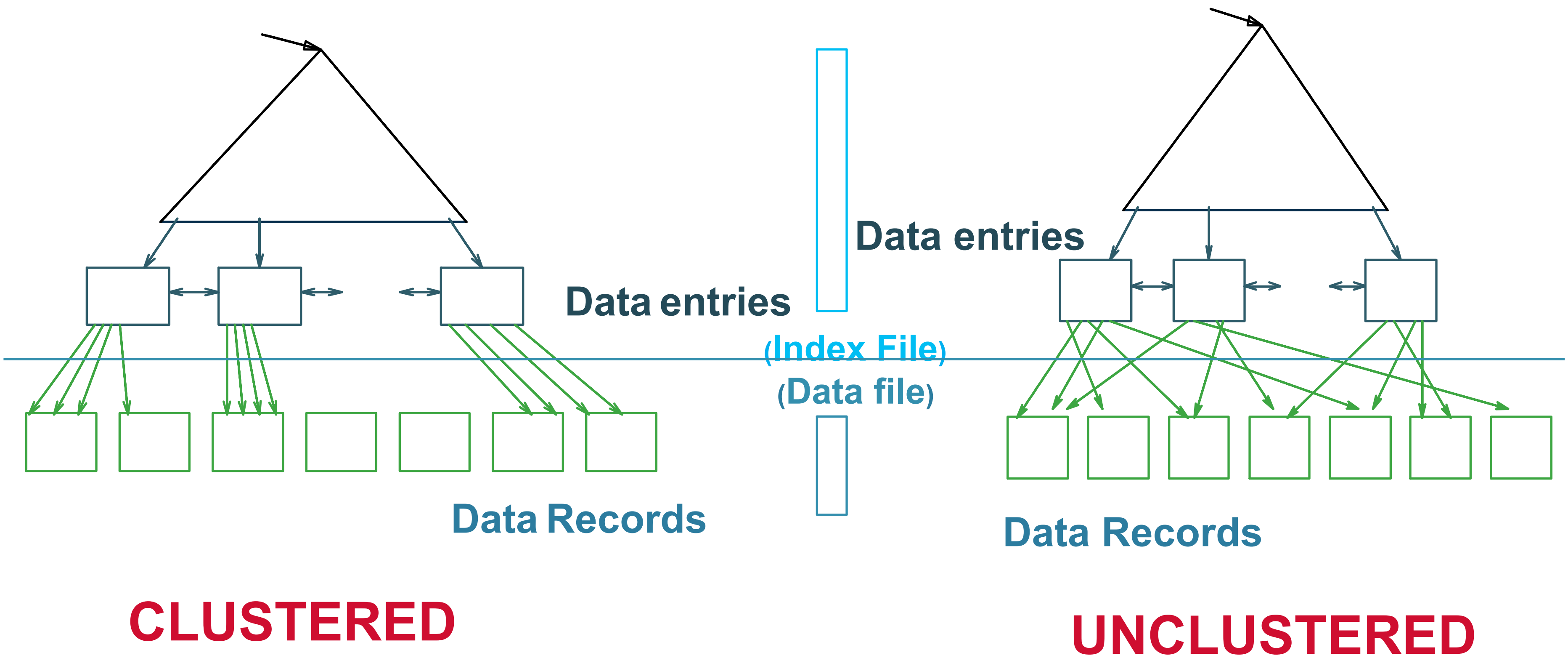
Tree-Based Index

- How many index levels do we need?
- Can we create them automatically? Yes!
- Can do something even more powerful!

B+ Trees

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

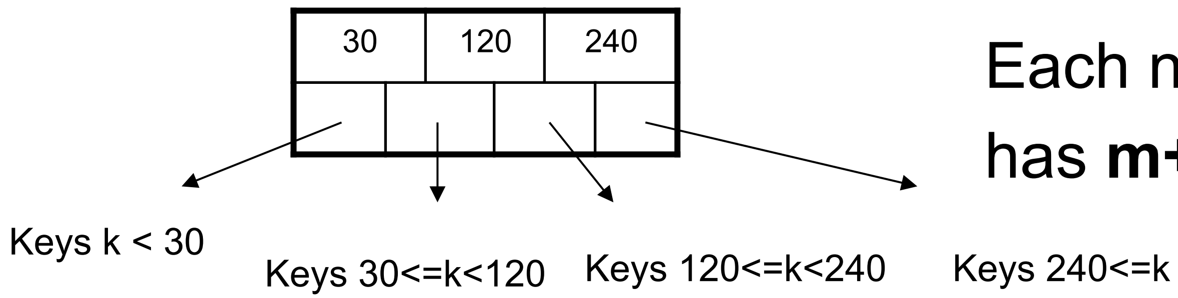
B+ Trees



Note: can also store data records directly as data entries

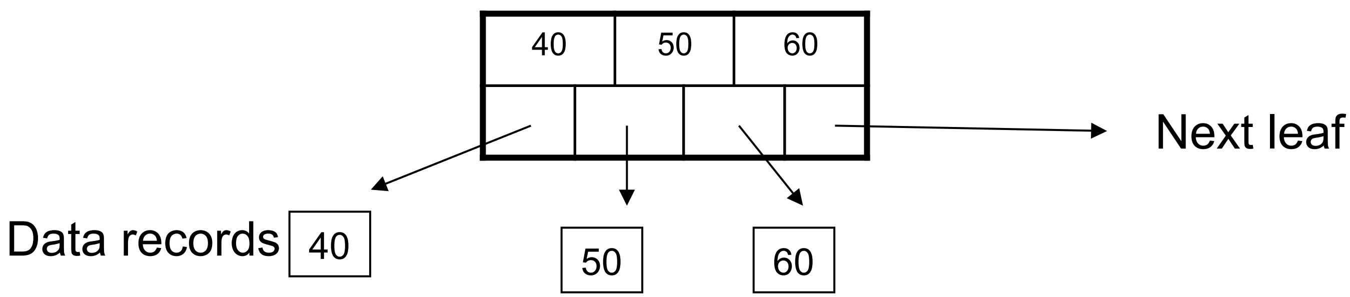
B+ Trees Basics

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



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

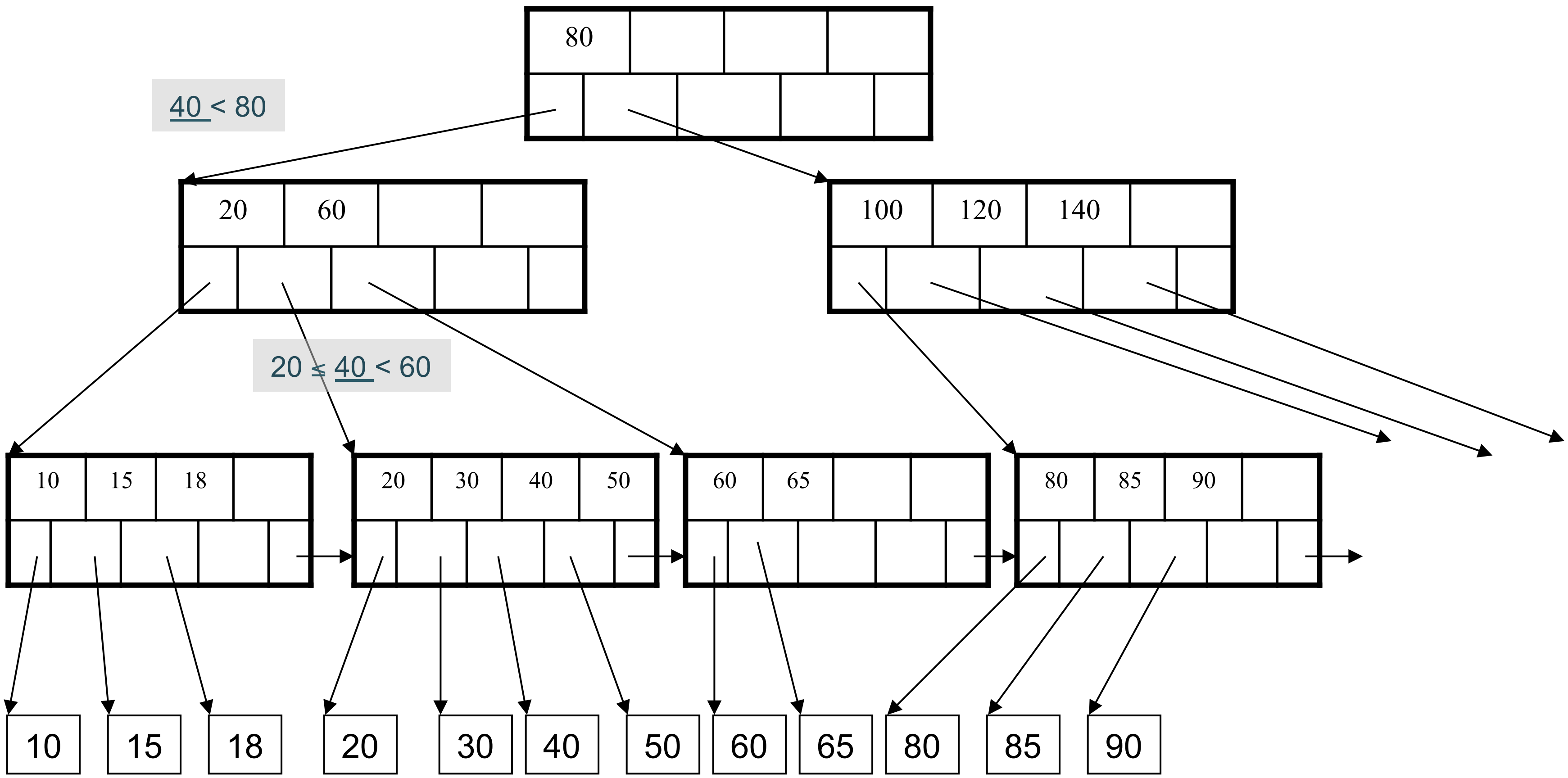
- Each leaf has **d <= m <= 2d keys**:



B+ Tree Example

d = 2

Find the key 40



Searching a B+ Tree

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

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

- Range queries:
  - Find lowest bound as above
  - Then sequential traversal

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

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

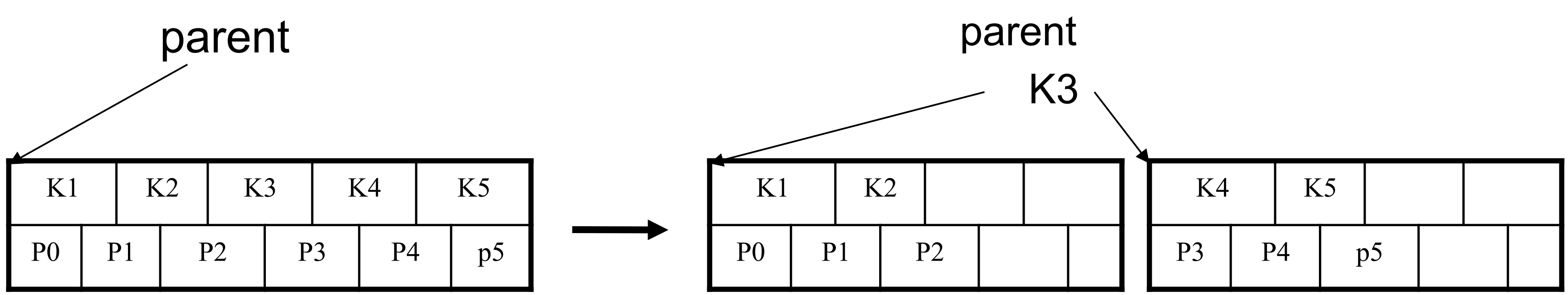
B+ Trees in Practice

- 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)

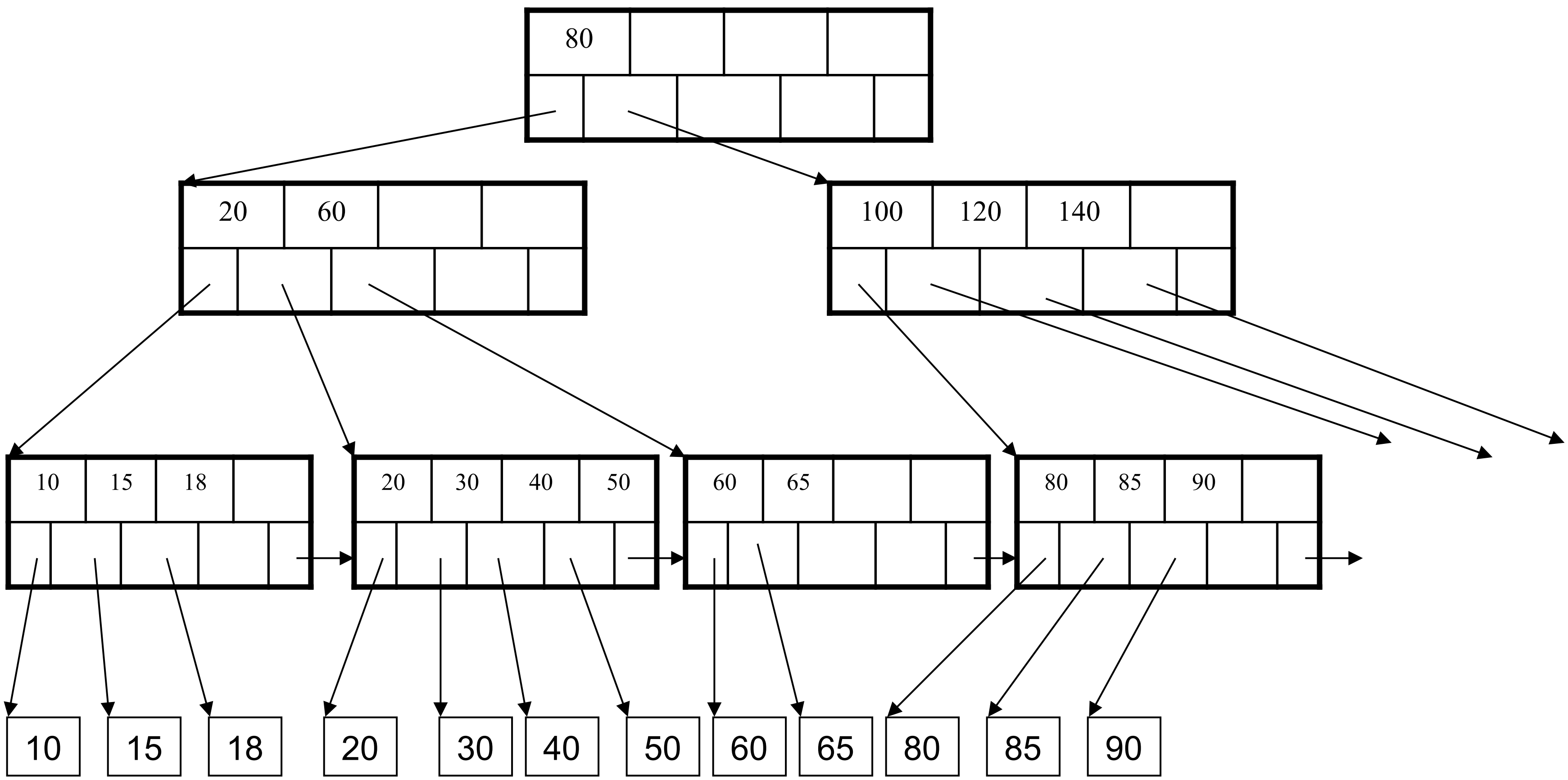
- Find leaf where K belongs, insert
- If no overflow (2d keys or less), halt
- If overflow (2d+1 keys), split node, insert in parent:



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

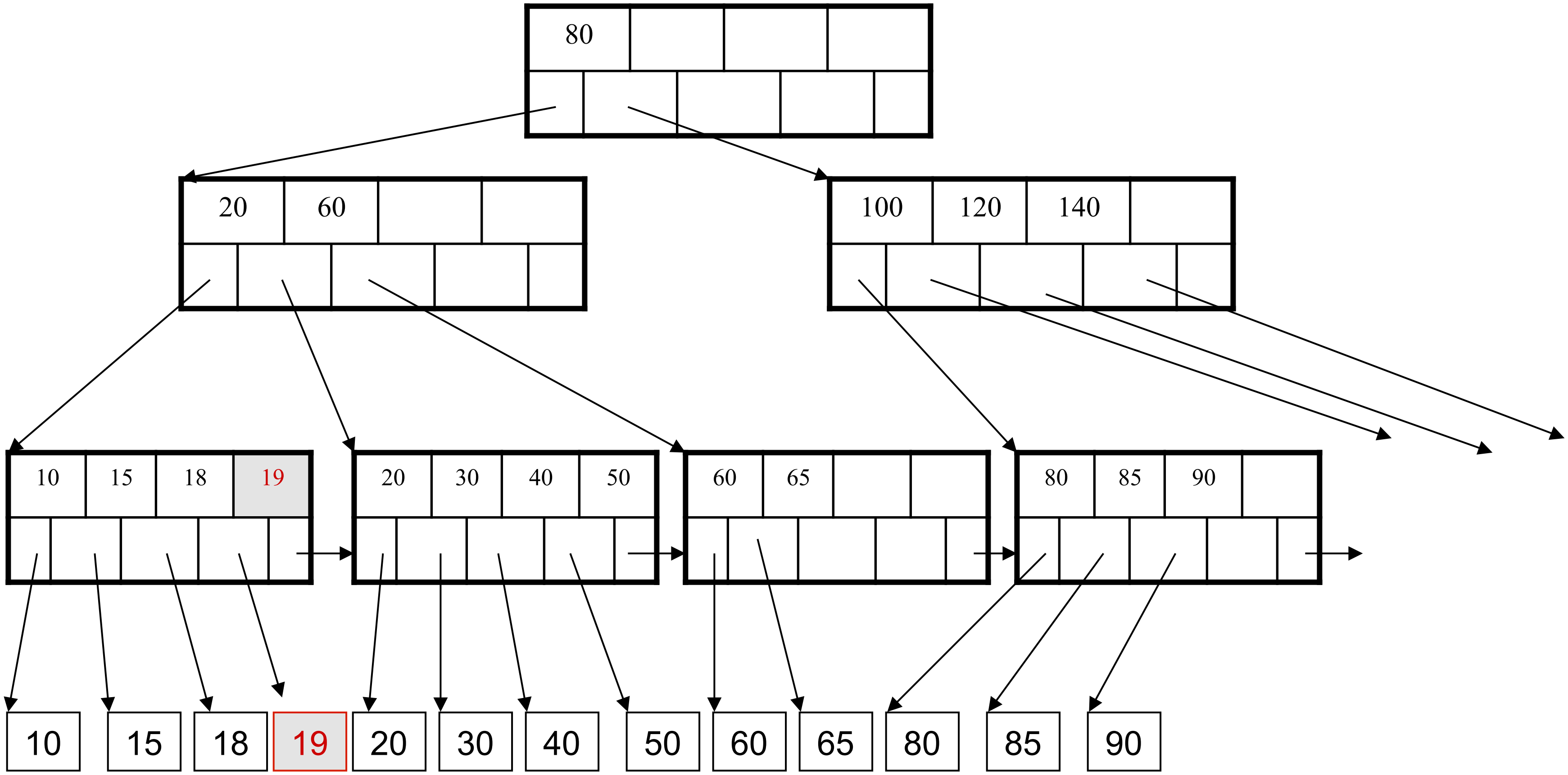
Insertion in a B+ Tree

Insert K=19



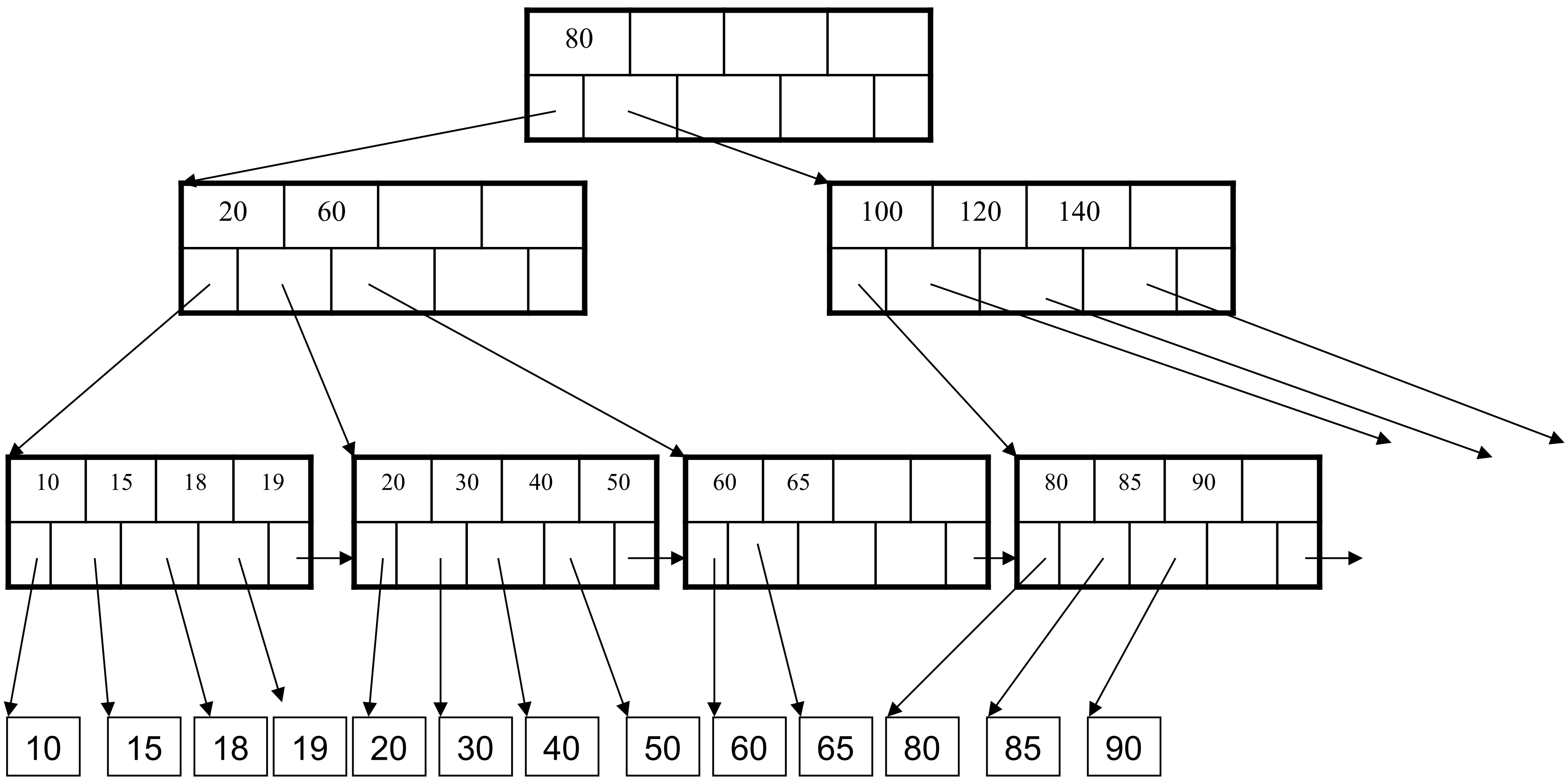
Insertion in a B+ Tree

After insertion



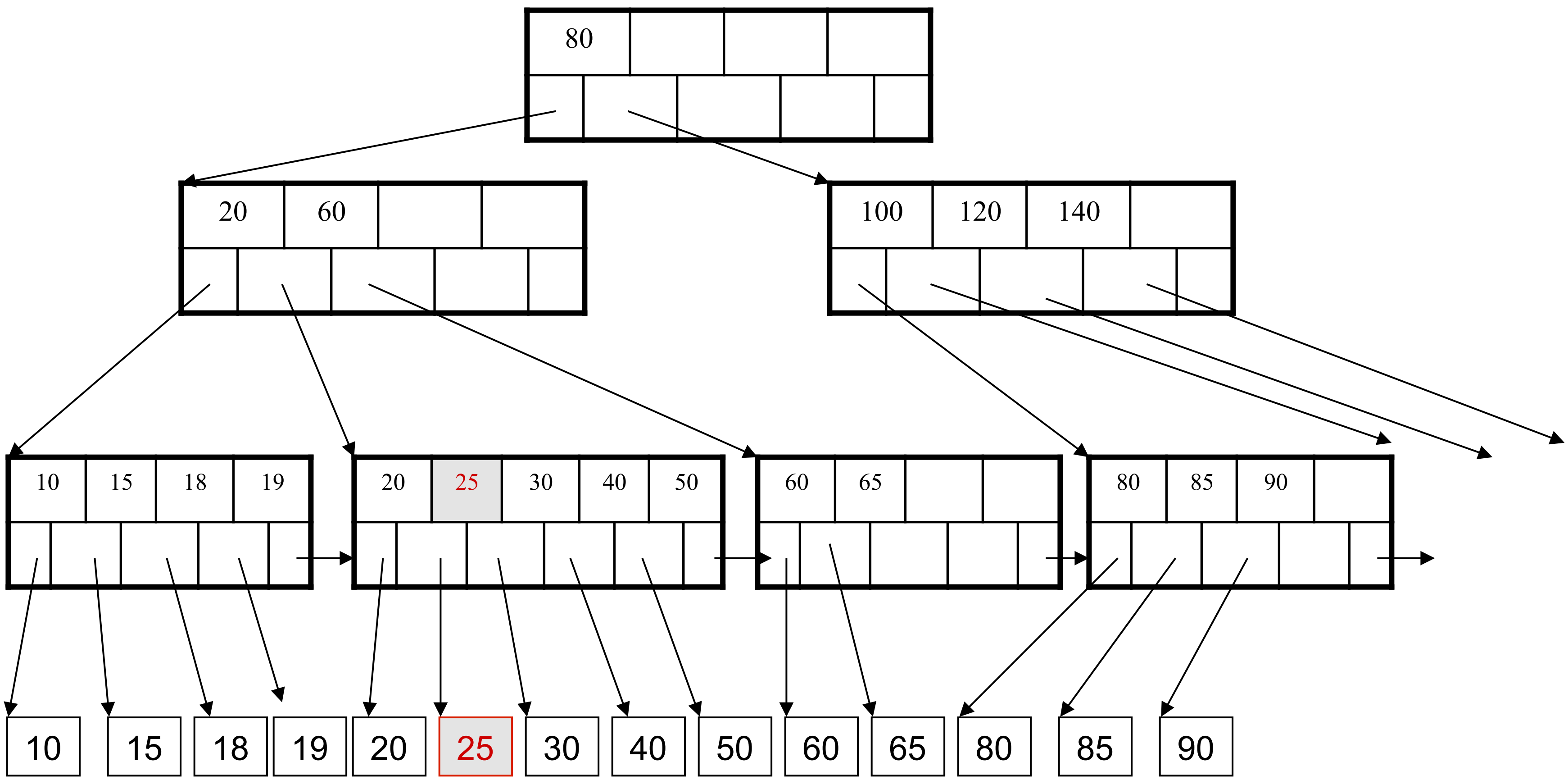
Insertion in a B+ Tree

Now insert 25



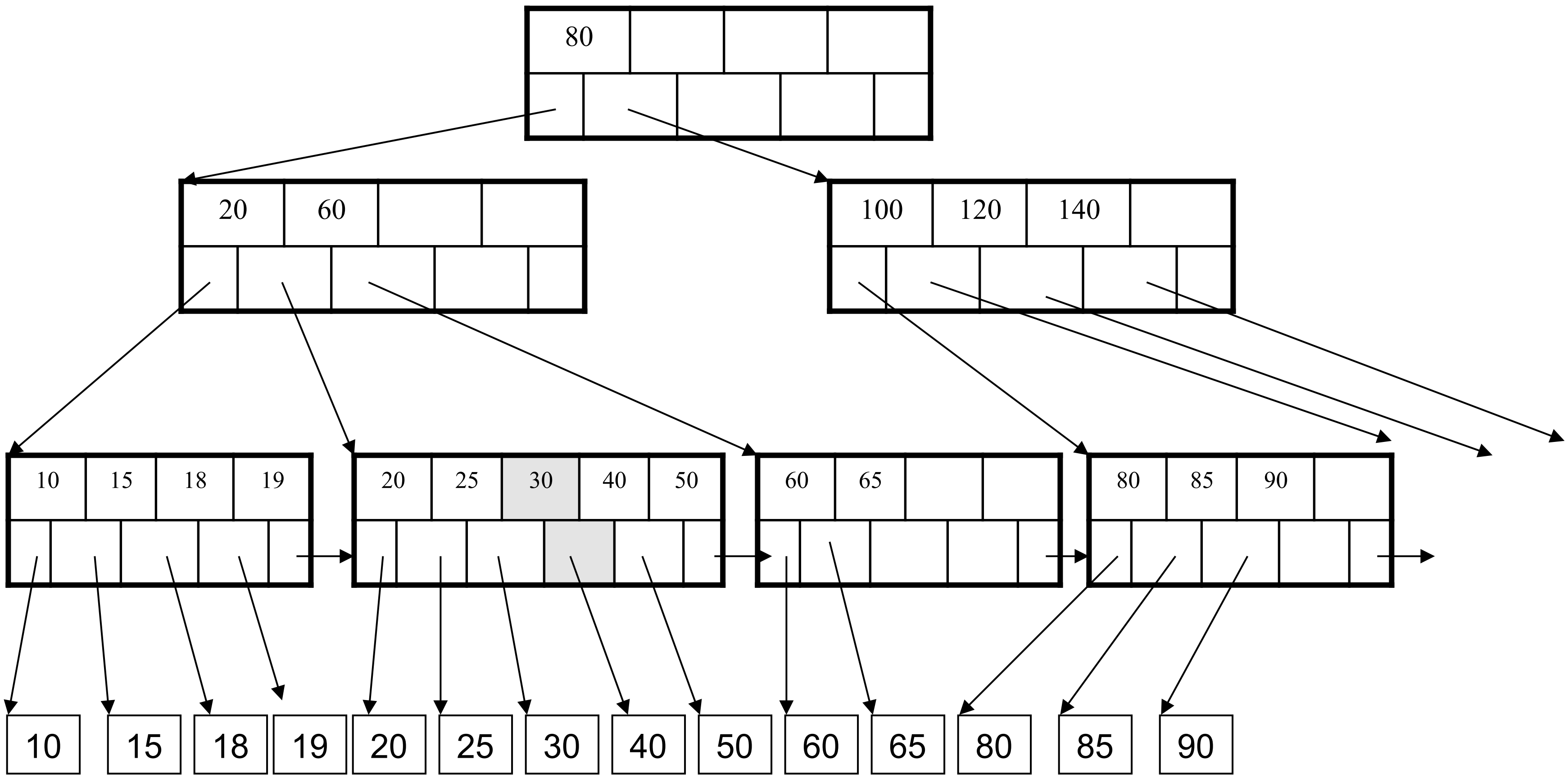
Insertion in a B+ Tree

After insertion



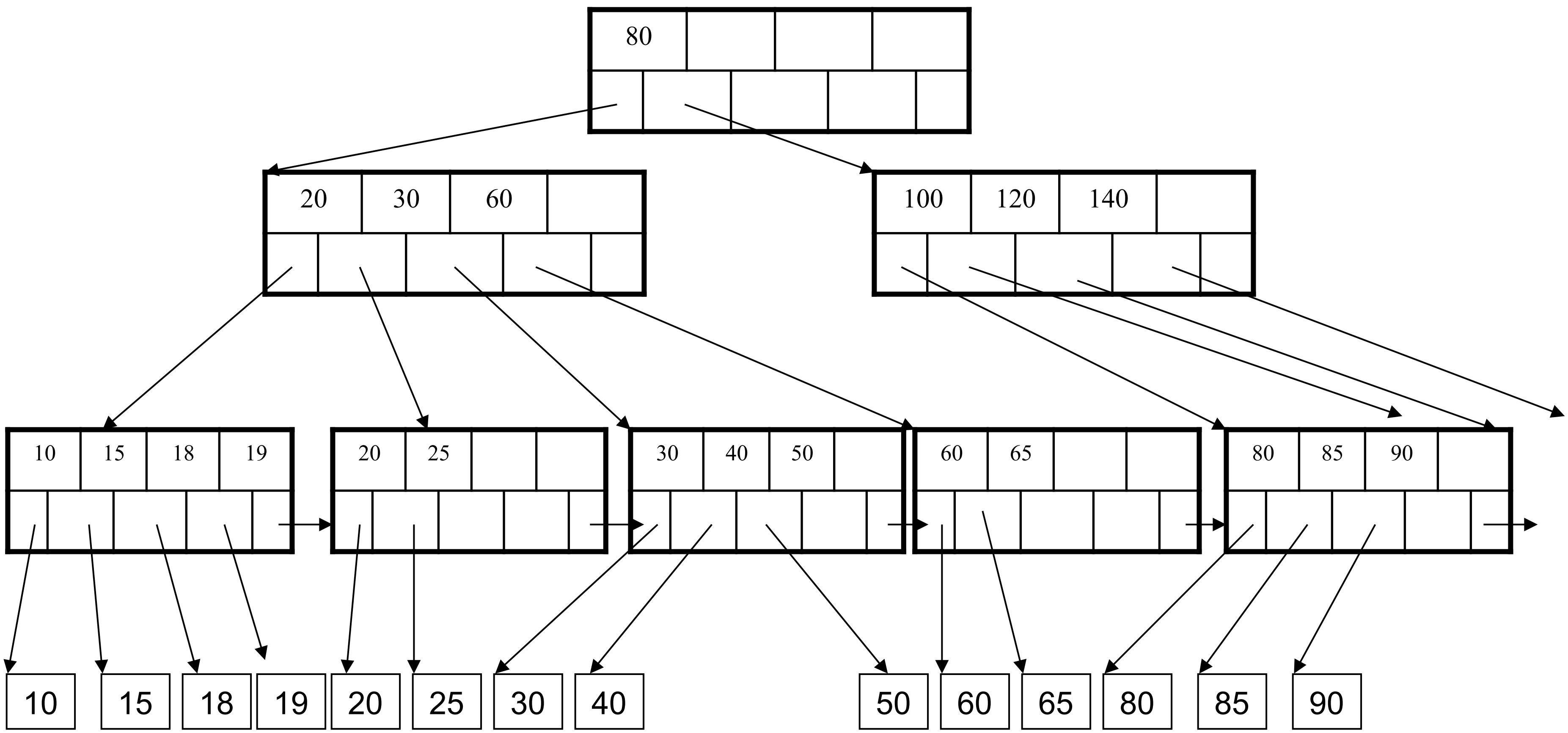
Insertion in a B+ Tree

But now have to split !



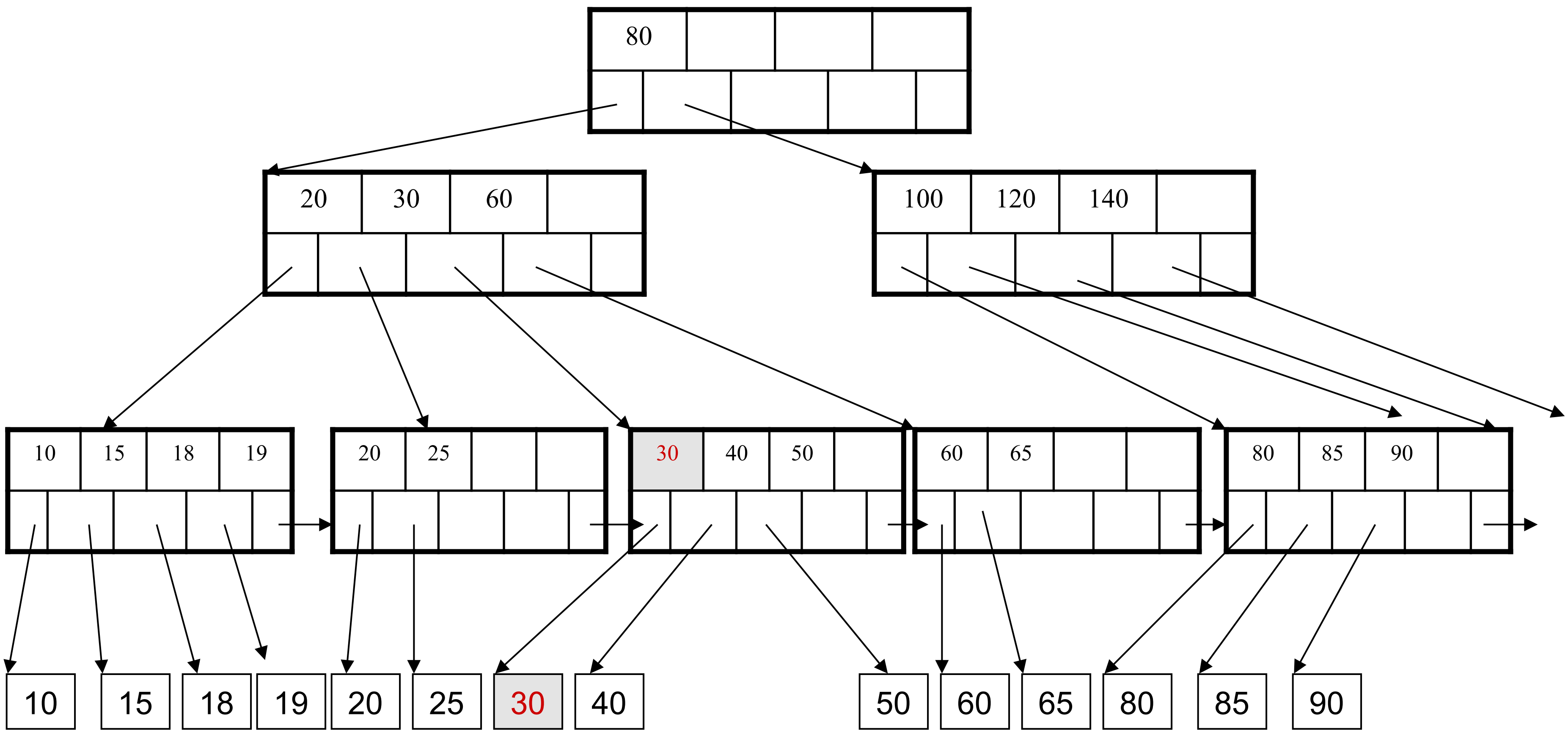
Insertion in a B+ Tree

After the split



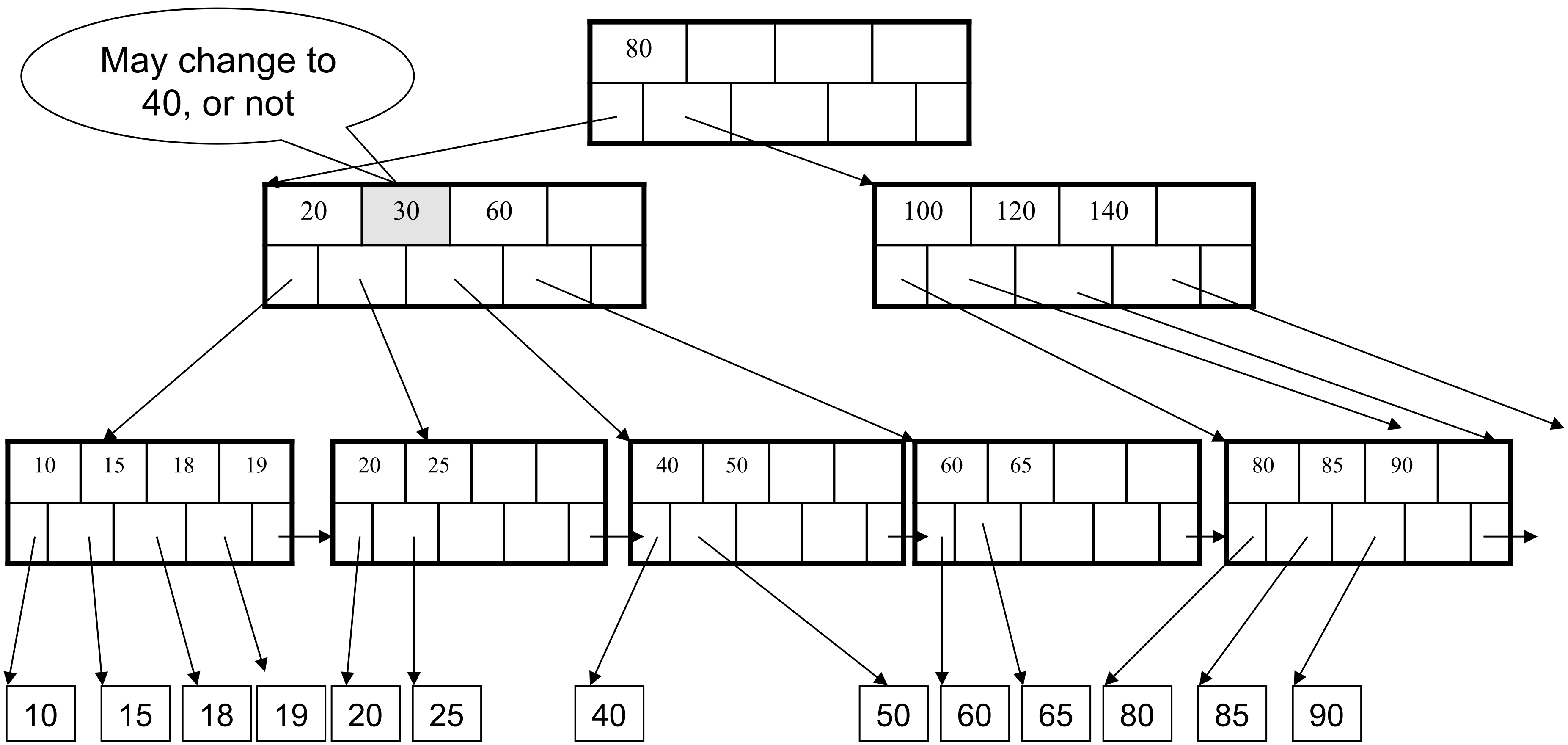
Deletion from a B+ Tree

Delete 30



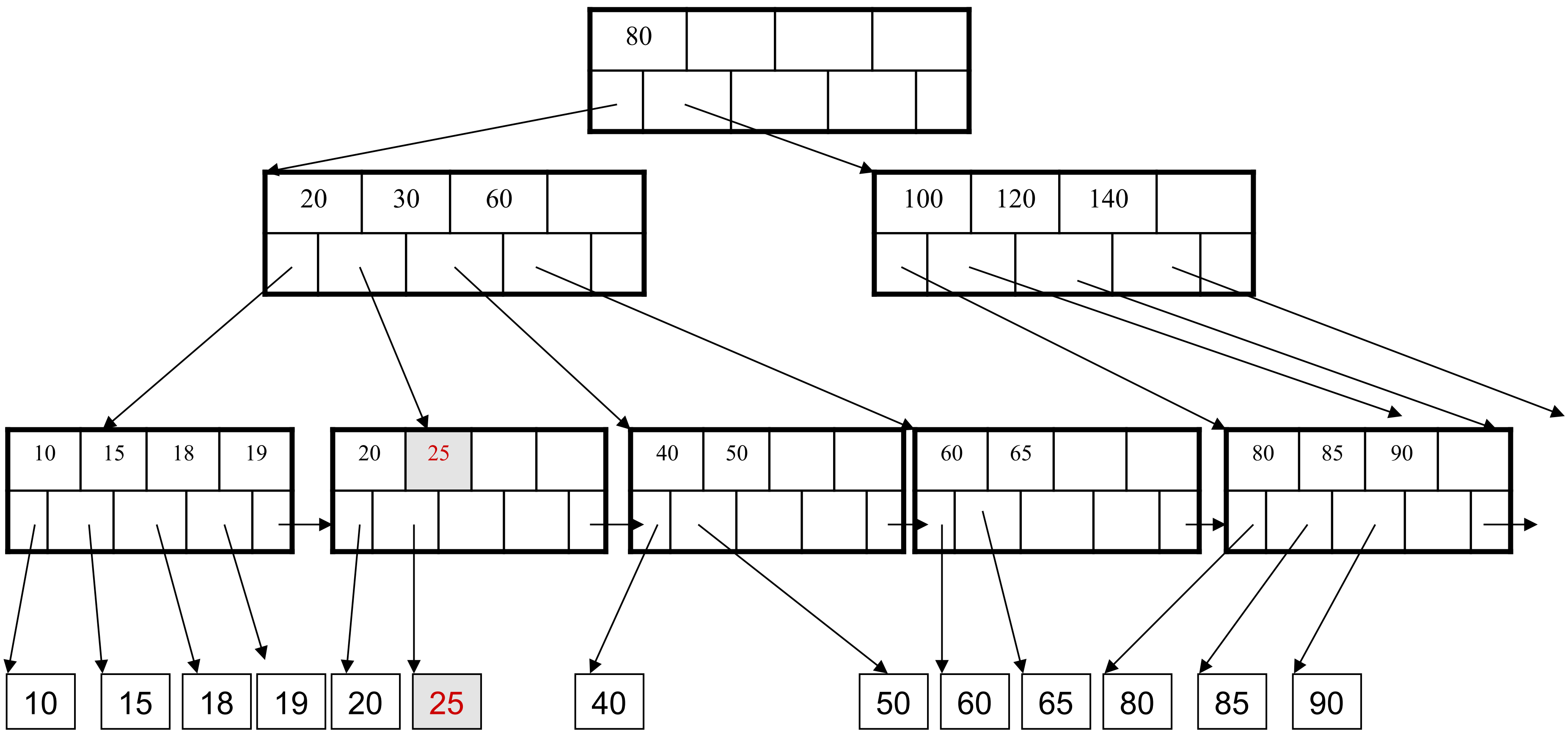
Deletion from a B+ Tree

After deleting 30



Deletion from a B+ Tree

Now delete 25

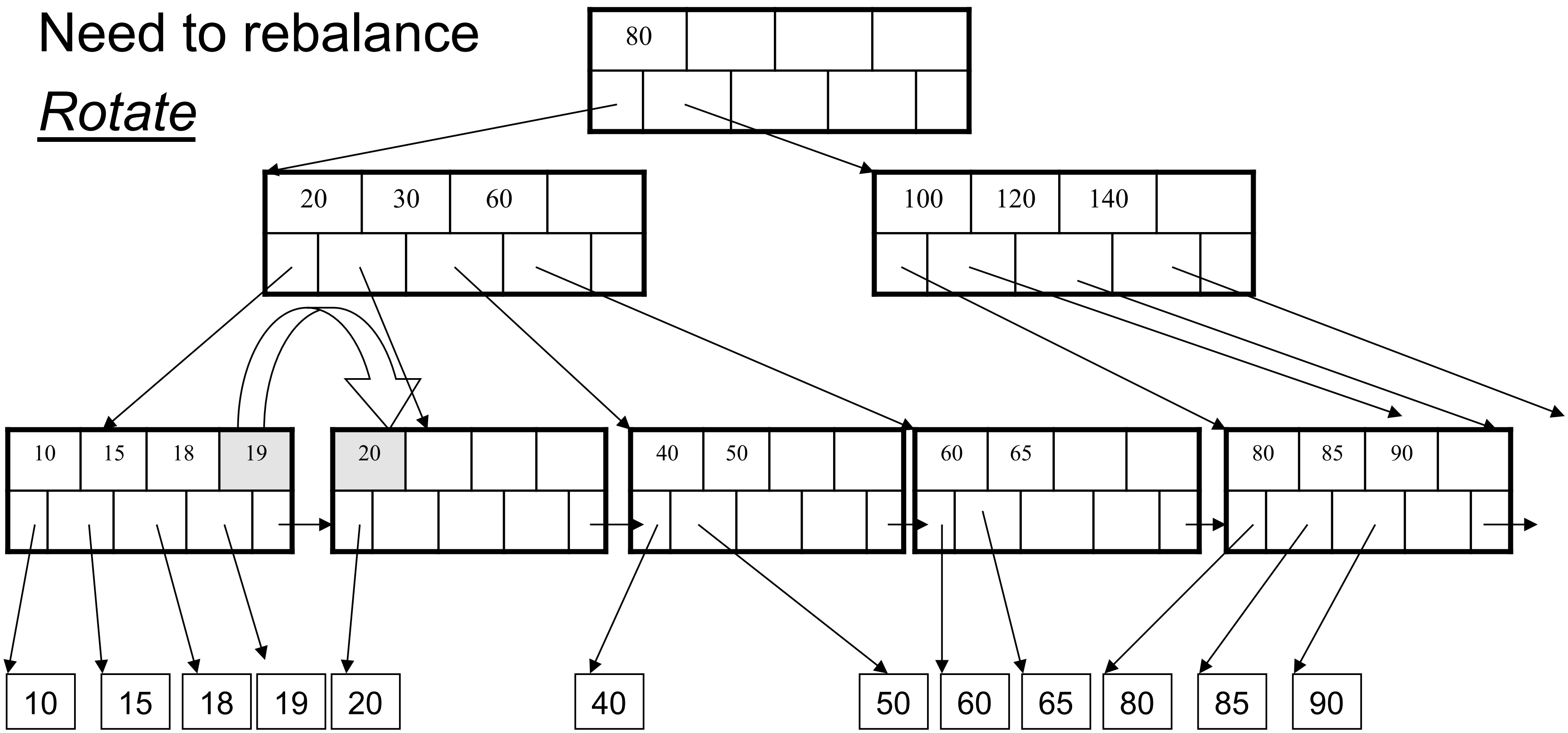


Deletion from a B+ Tree

After deleting 25

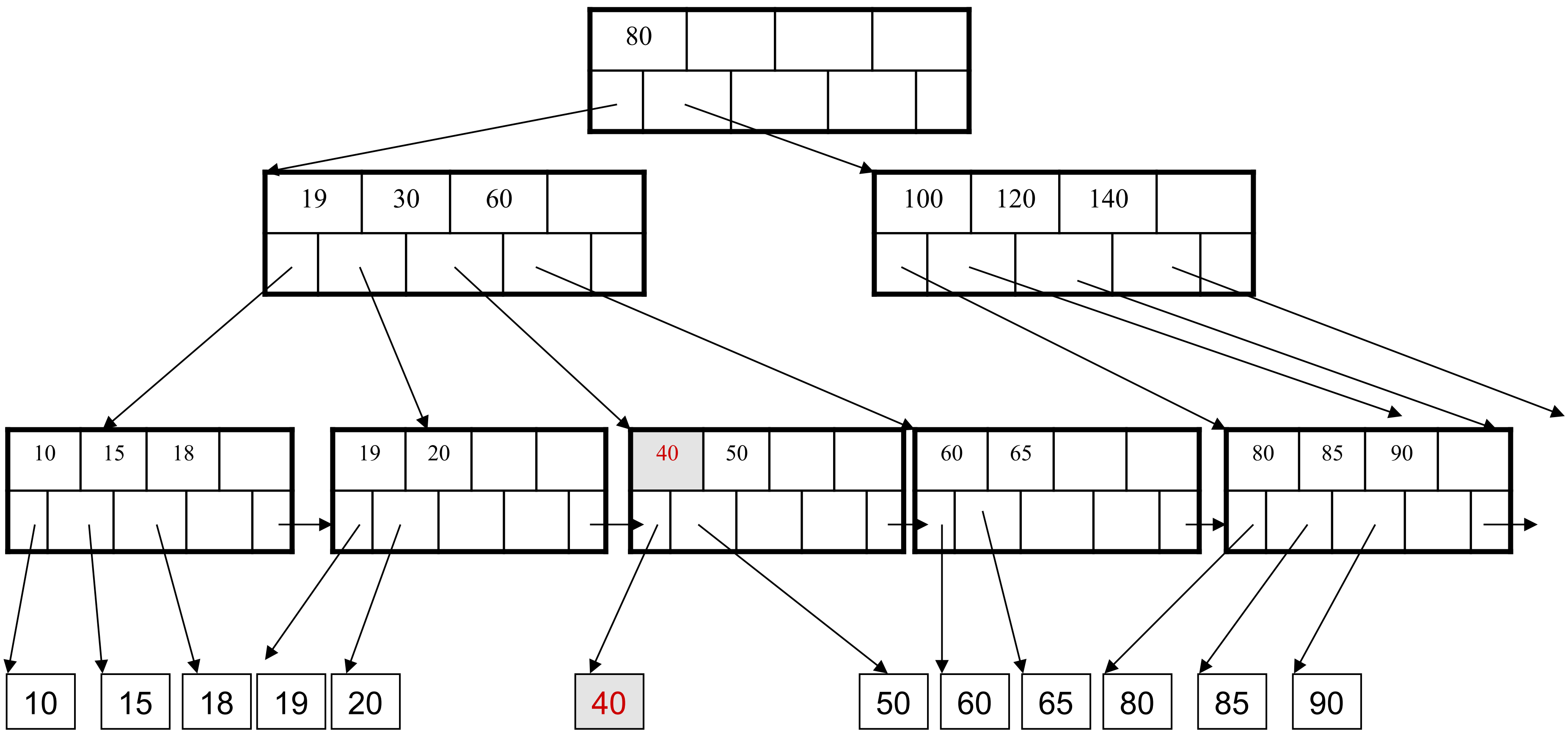
Need to rebalance

Rotate



Deletion from a B+ Tree

Now delete 40

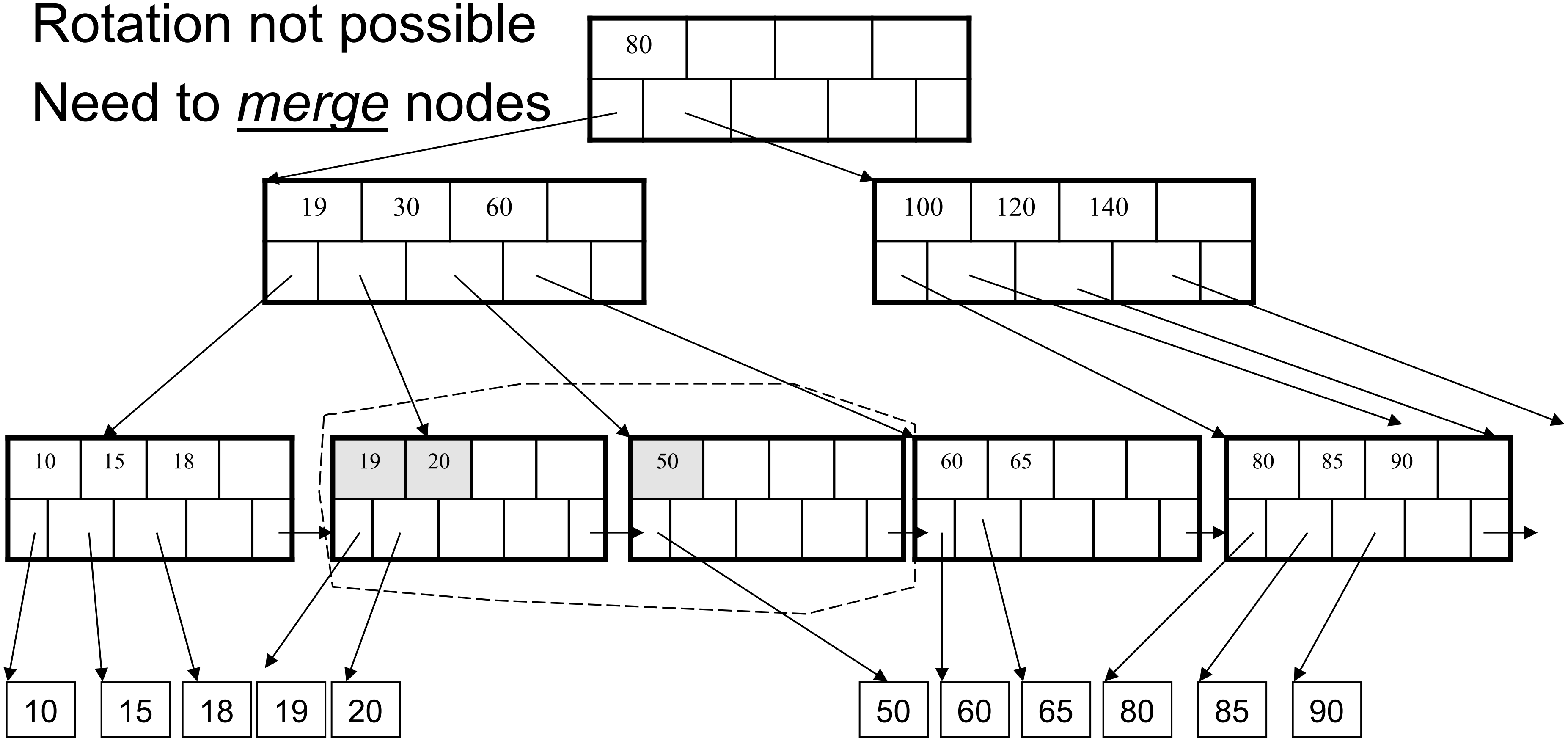


Deletion from a B+ Tree

After deleting 40

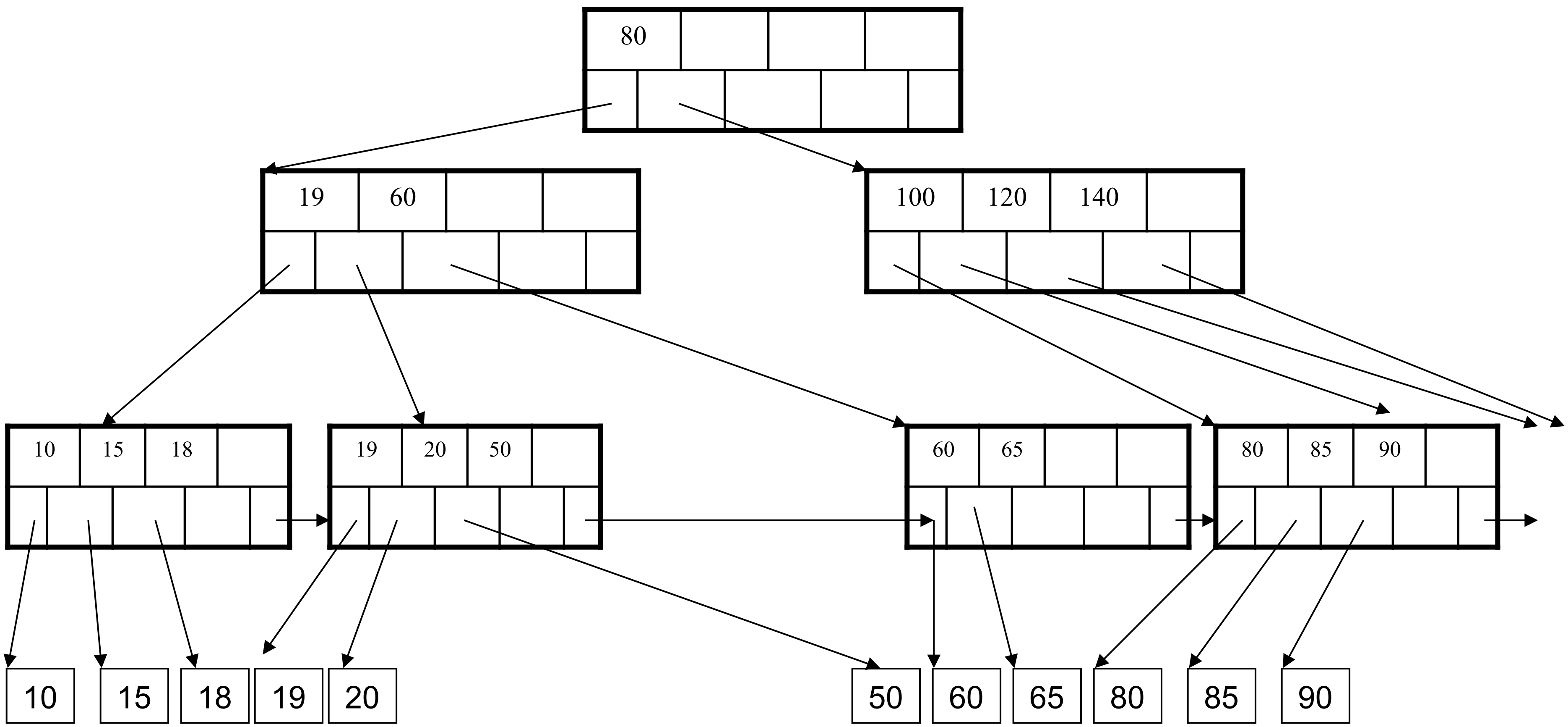
Rotation not possible

Need to *merge* nodes



Deletion from a B+ Tree

Final tree



Summary on B+ Trees

- Default index structure on most DBMSs
- 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

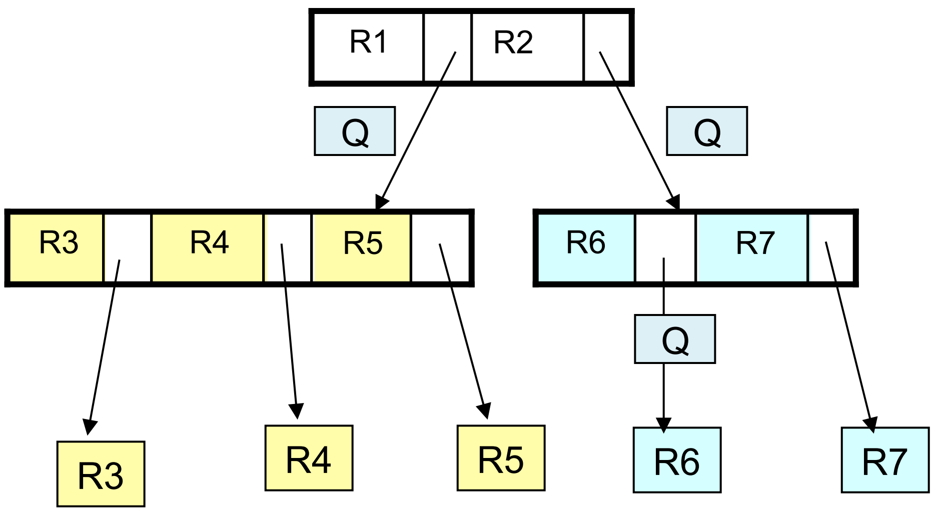
Optional Material

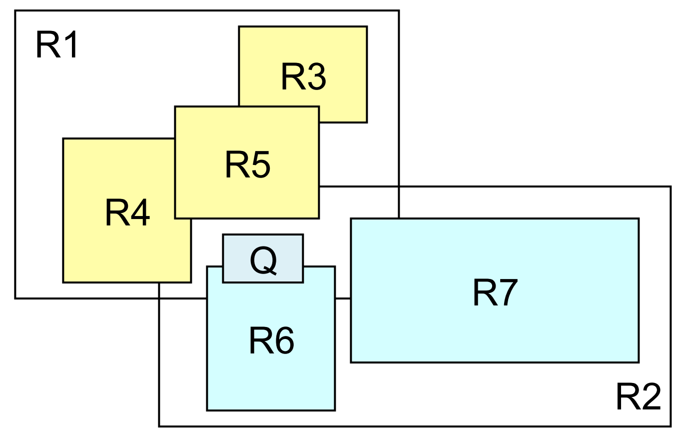
- Let's take a look at another example of an index….

R-Tree Example

Designed for spatial data

Search key values are bounding boxes





For insertion: at each level, choose child whose bounding box needs least enlargement (in terms of area)