CSE 444: Database Internals

Lectures 5-6

Indexing

Announcements

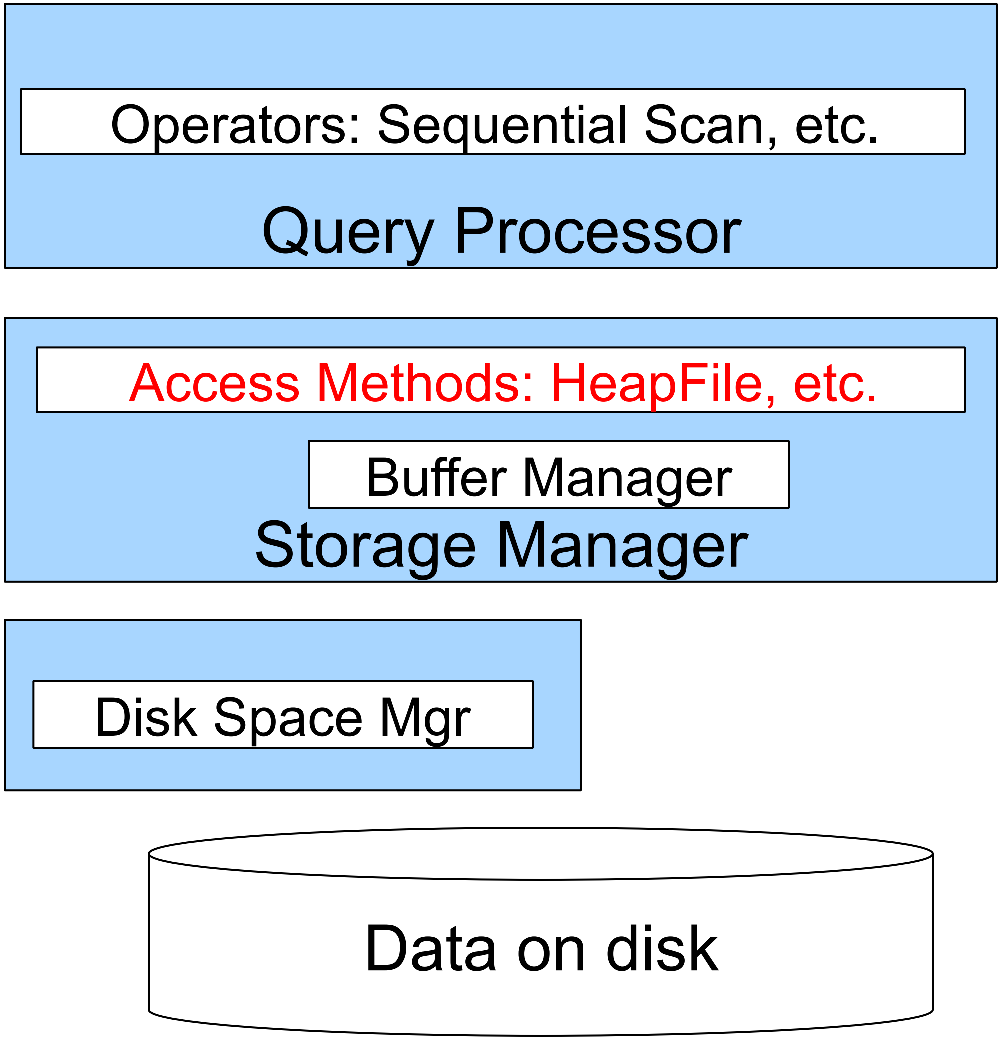
- HW1 due tonight by 11pm
  - Turn in an electronic copy (word/pdf) by 11pm, or
  - Turn in a hard copy in my office by 4pm
- Lab1 is due Friday, 11pm
  - Do not fall behind on the labs! They build on each other

Access Methods

Last lecture, we learned that:

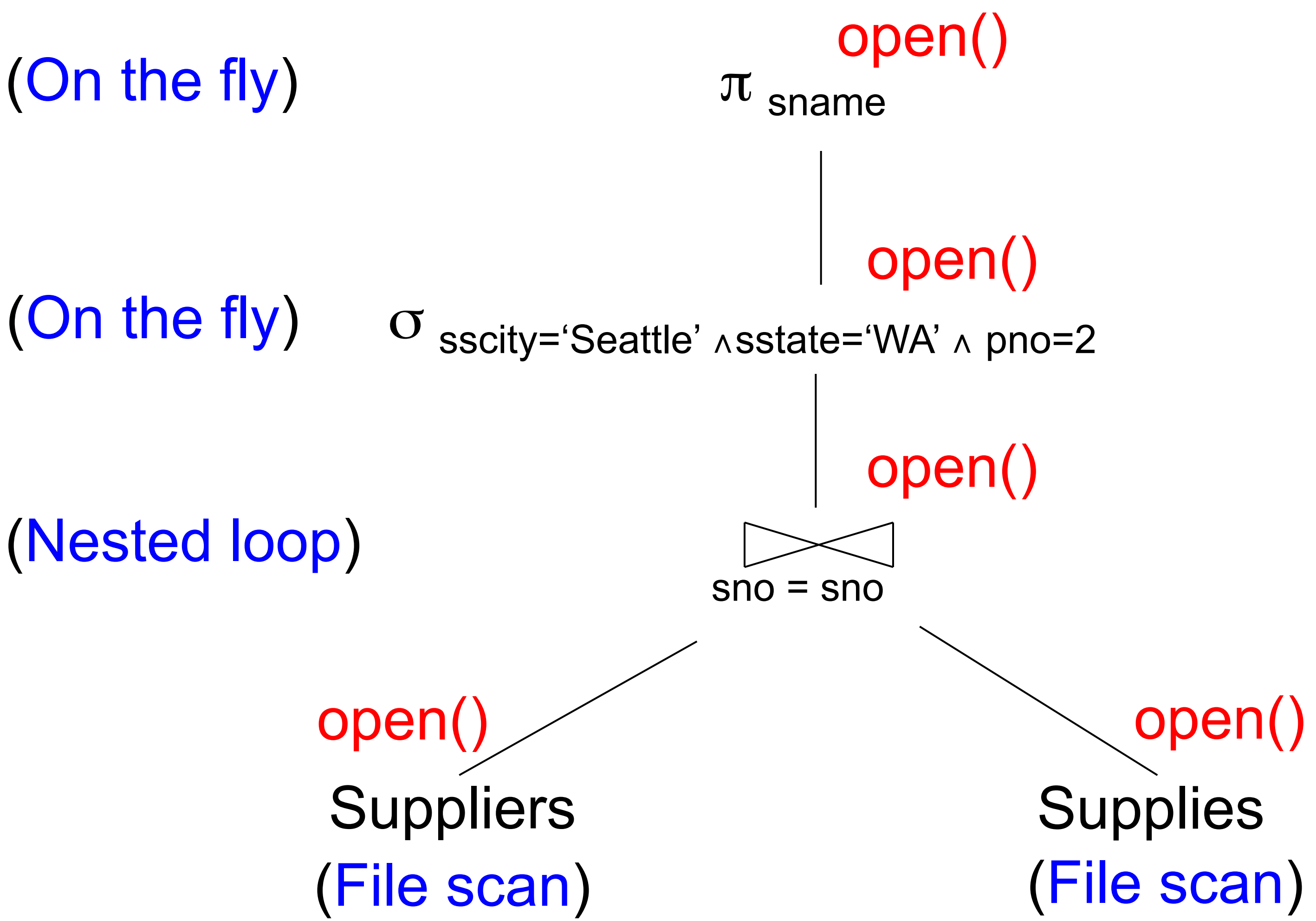
- A DBMS stores data on disk by breaking it into *pages*
  - A page is the size of a disk block.
  - A page is the unit of disk IO
- Buffer manager caches these pages in memory
- Access methods do the following:
  - They organize pages into collections called DB *files*
  - They organize data inside pages
  - They provide an API for operators to access data in these files
- We discussed OS vs DBMS files and buffer manager

Access Methods

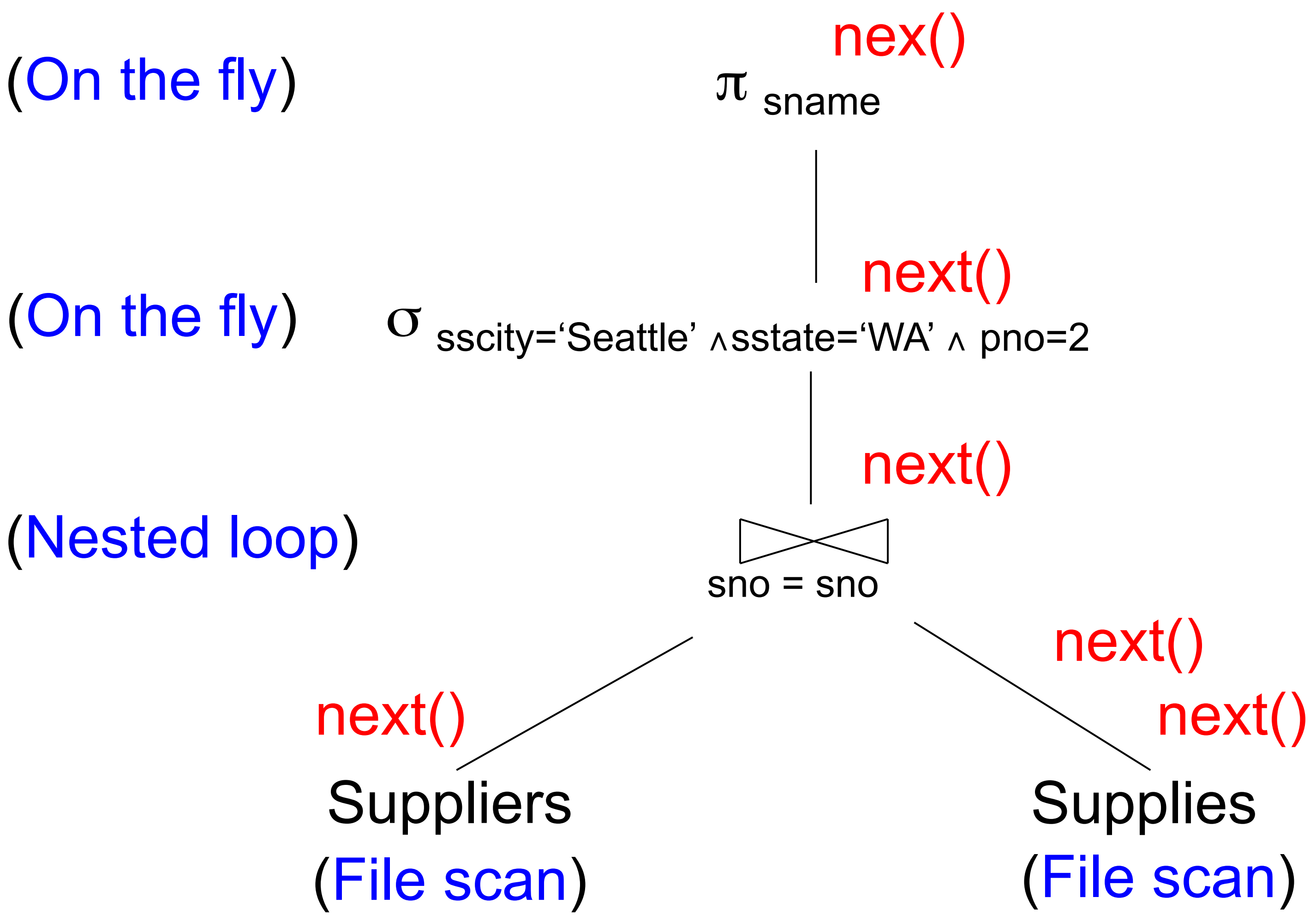


- **Operators:** Process data
- **Access methods**: Organize data to support fast access to desired subsets of records
- **Buffer manager**: Caches data in memory. Reads/ writes data to/from disk as needed
- **Disk-space manager**: Allocates space on disk for files/access methods

Query Execution
How it all Fits Together



Query Execution
How it all Fits Together



Query Execution
How it all Fits Together

open()

nex()

SeqScan

Operator at bottom of plan

open()

nex()

In SimpleDB, SeqScan can find HeapFile in Catalogue

Heap File Access Method

Offers iterator interface

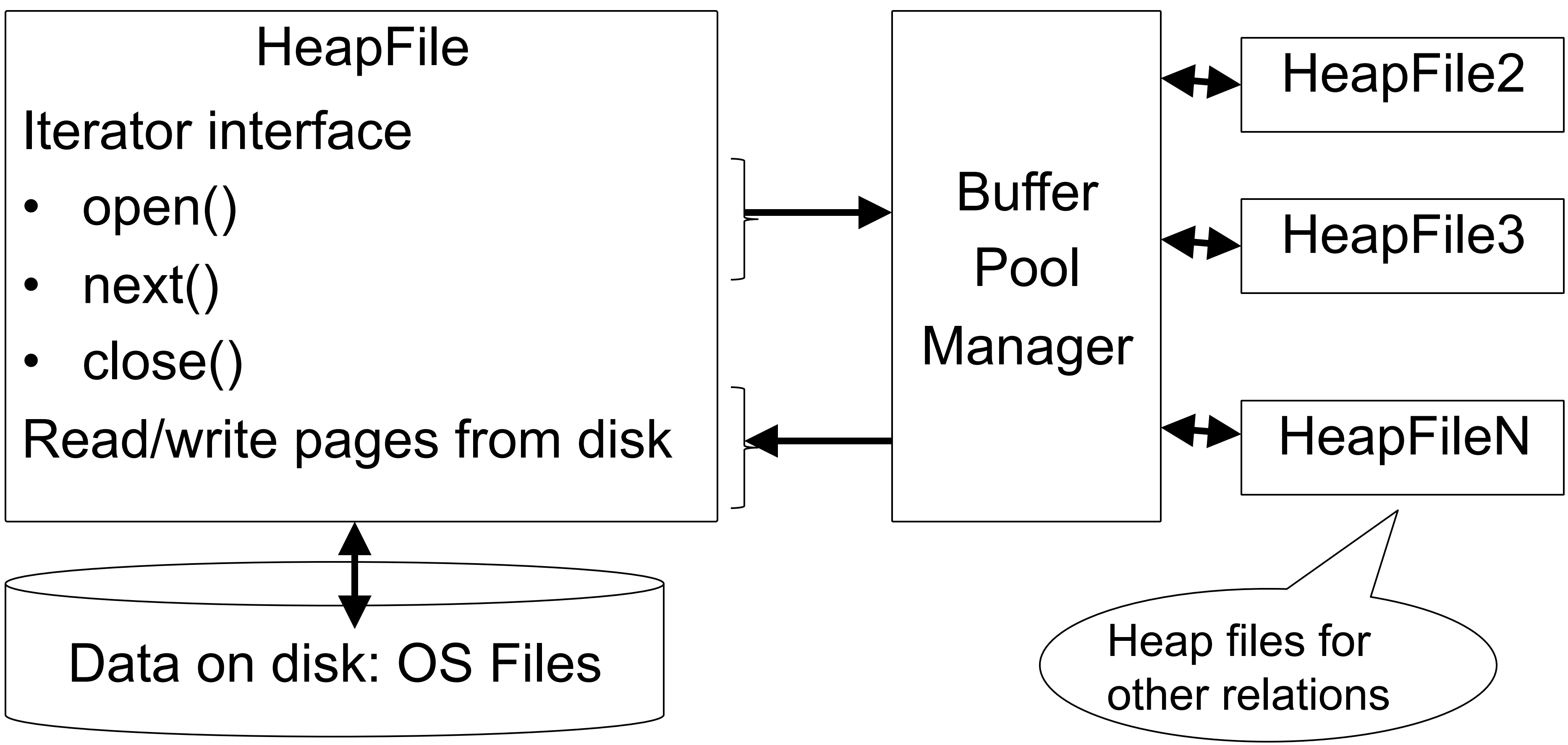
- open()
- next()
- close()

Knows how to read/write pages from disk

But if Heap File reads data directly from disk, it will not stay cached in Buffer Pool!

Query Execution
How it all Fits Together

Everyone shares a single cache



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

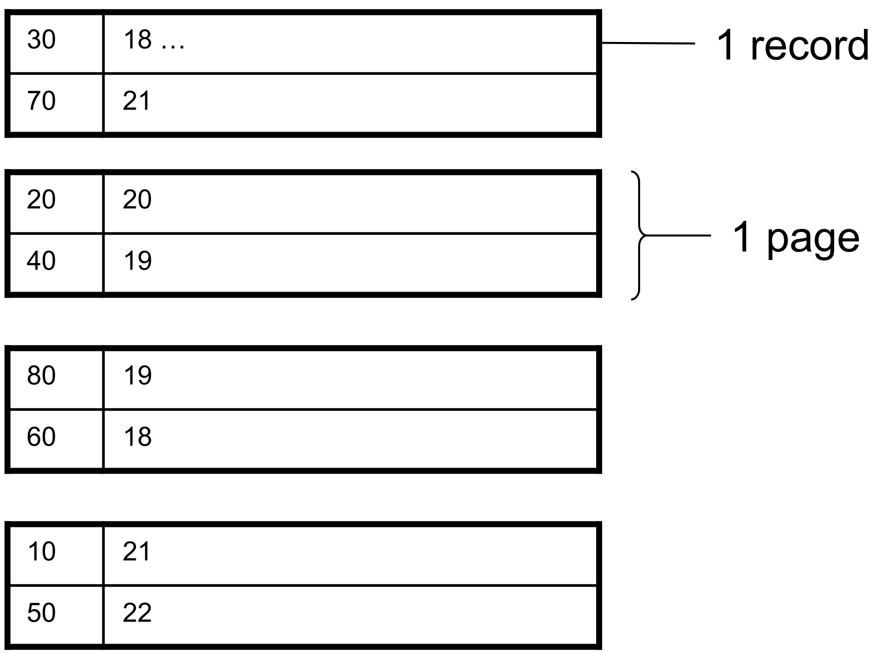
- Critical to support such requests efficiently
  - Why read all data form disk when we only need a small fraction of that data?

- 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 (Index structures, Hash-based indexes)

} Next time (B+ trees)

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

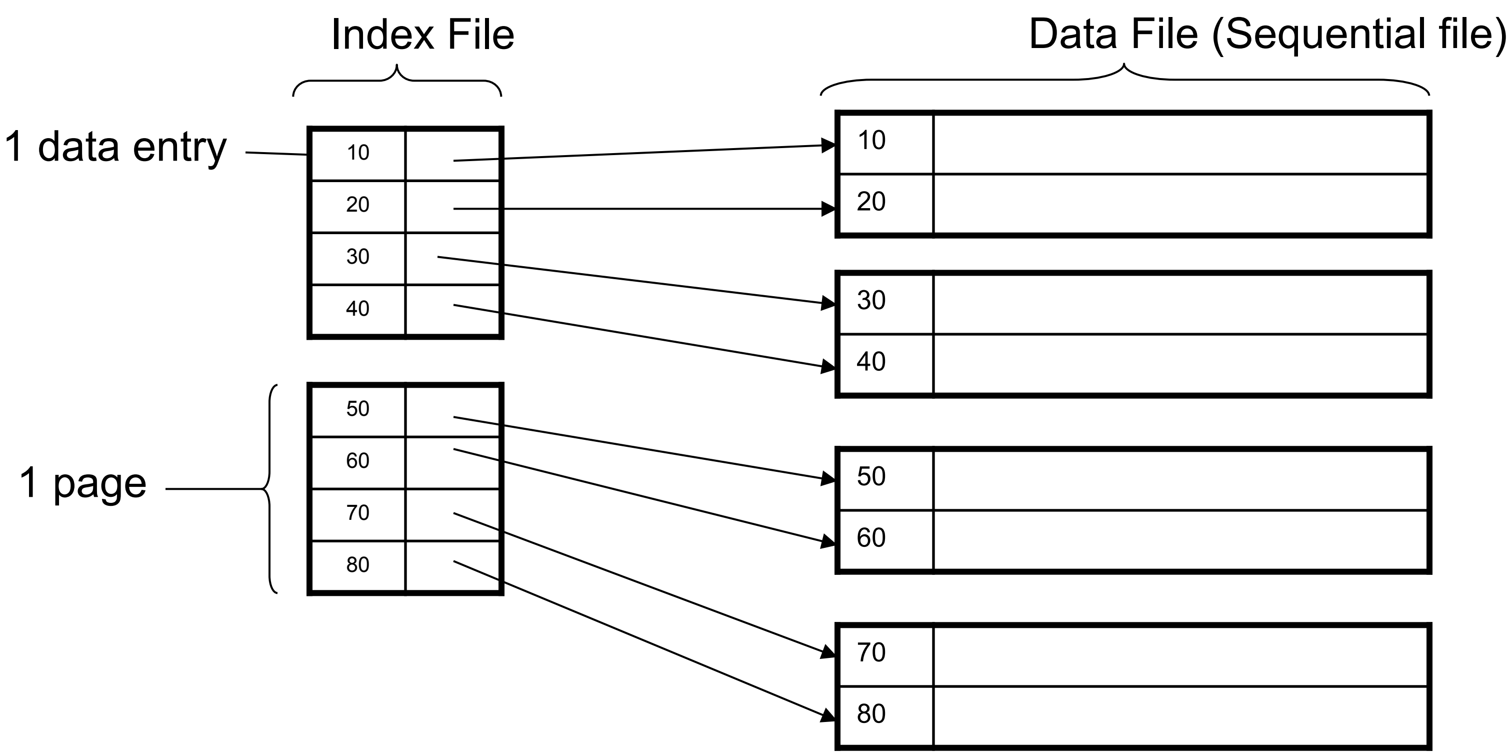
- **Search key** = can be any set of fields
  - not the same as the primary key, nor a key
- **Index** = collection of data entries
- **Data entry** for key k can be:
  - The actual record with key k
    - In this case, **the index is also a special file organization**
    - Called: "indexed file organization"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

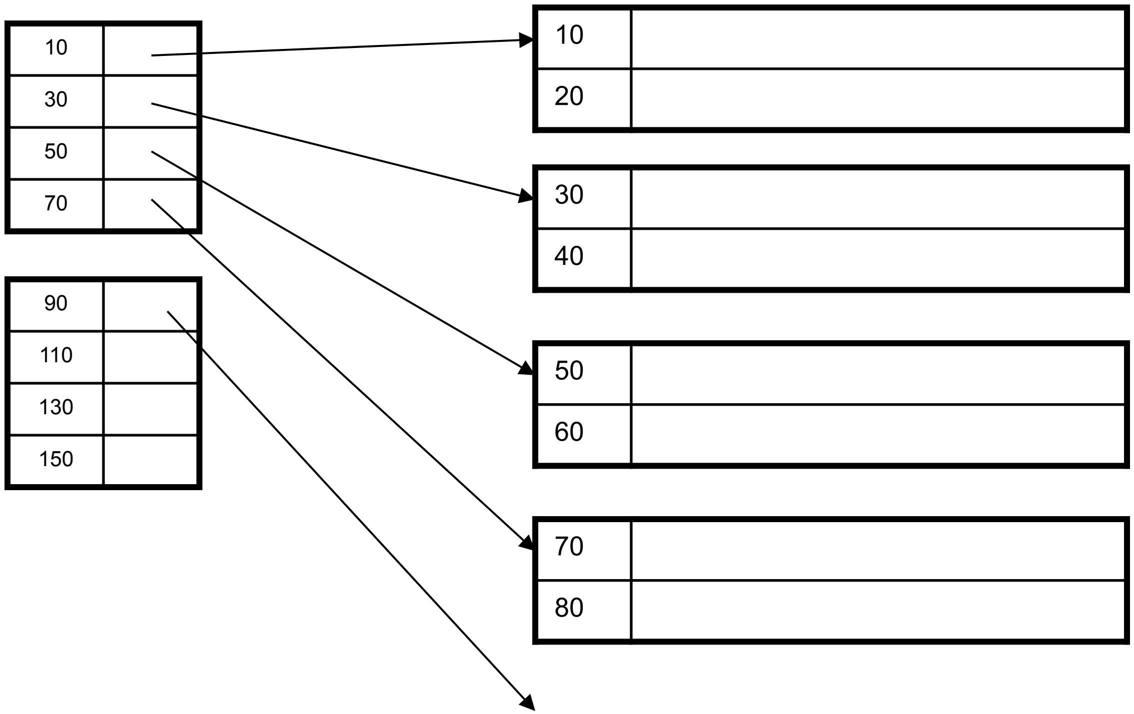
Primary Index

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



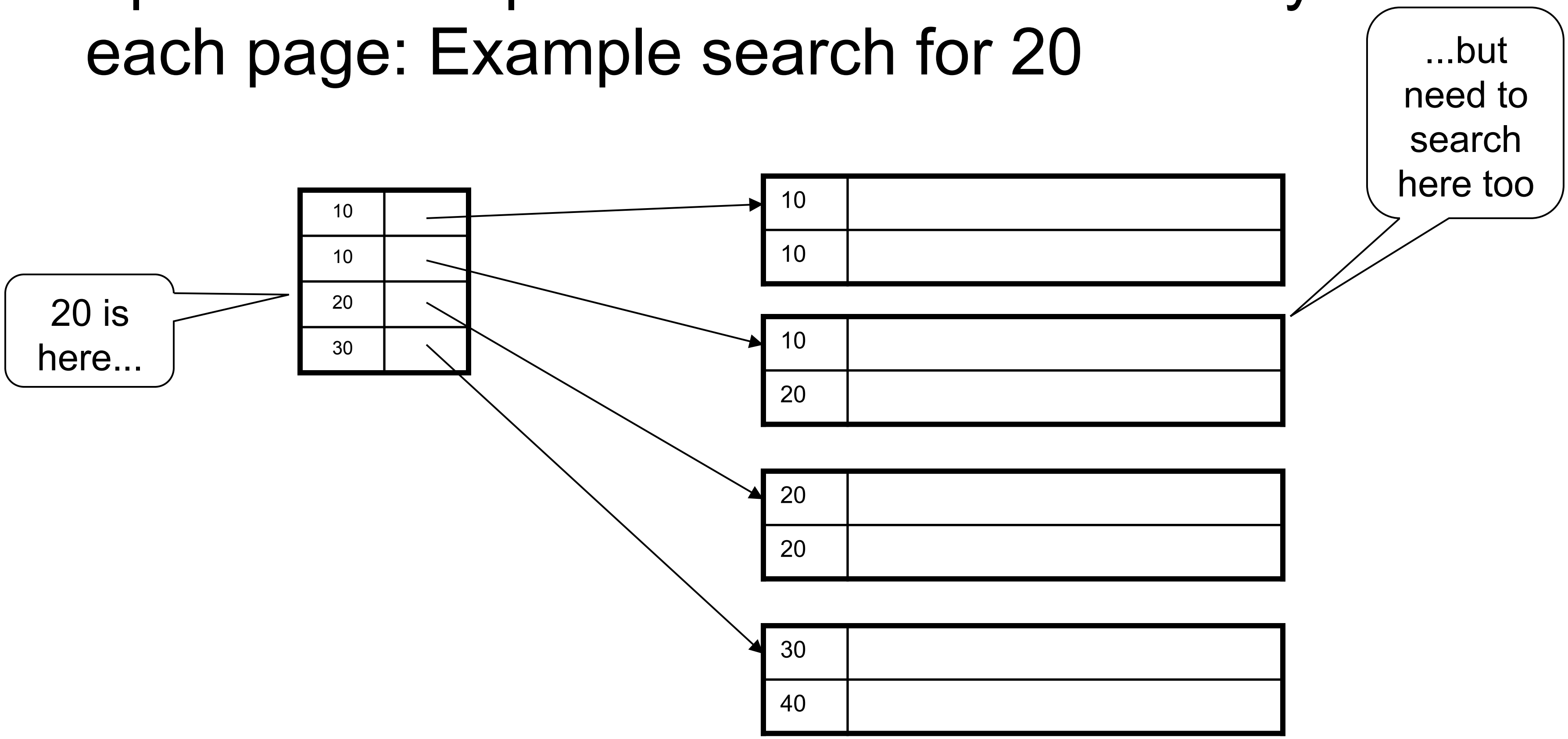
Primary Index

- *Sparse* index



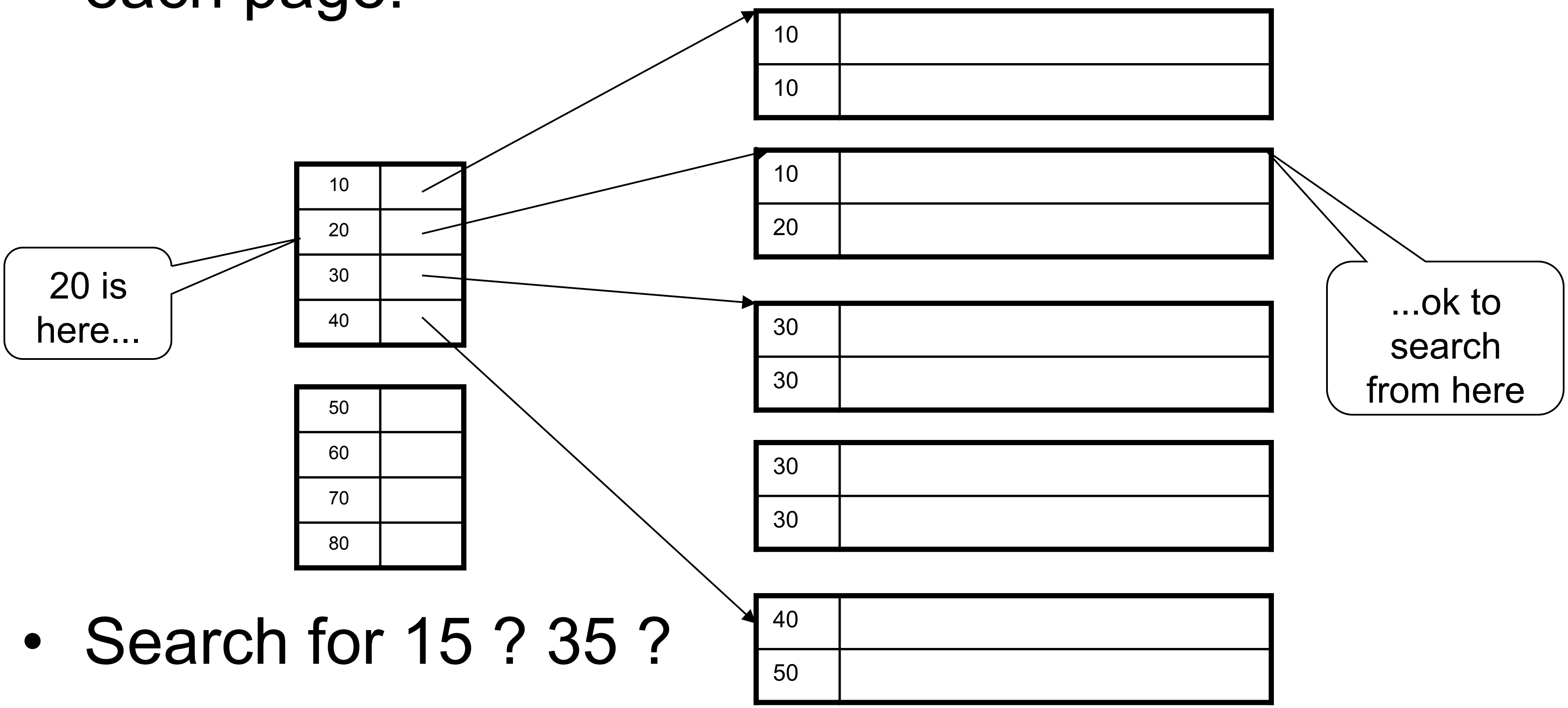
Primary Index with Duplicate Keys

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



Primary Index with Duplicate Keys

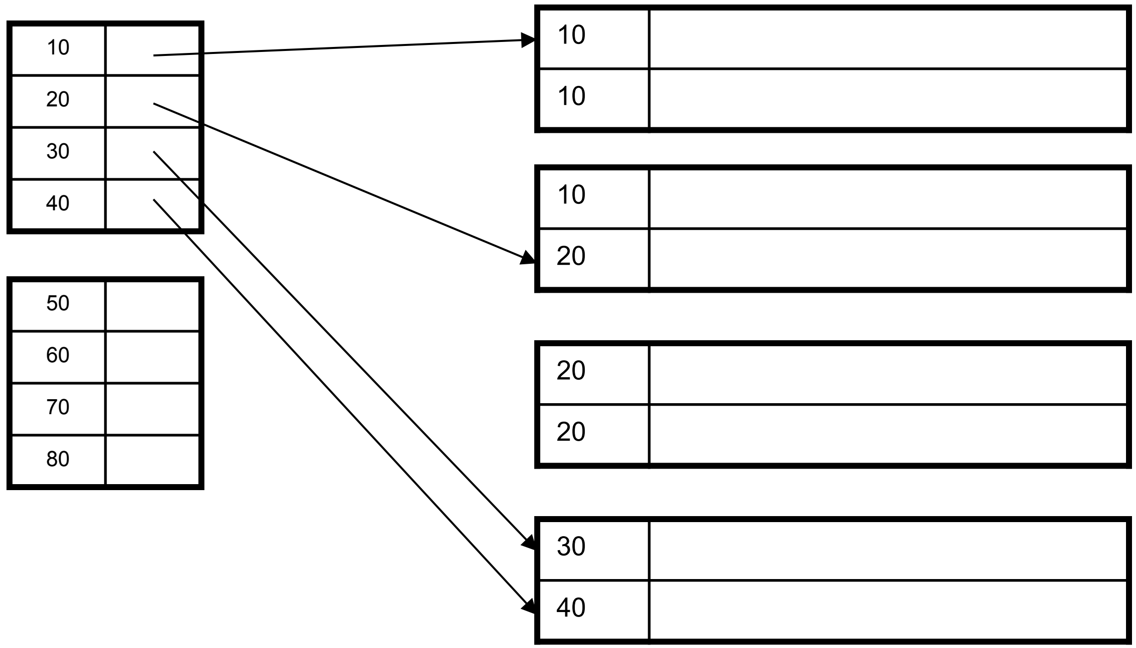
- Better: pointer to ***lowest new search key*** on each page:



- Search for 15 ? 35 ?

Primary Index with Duplicate Keys

- Dense index:

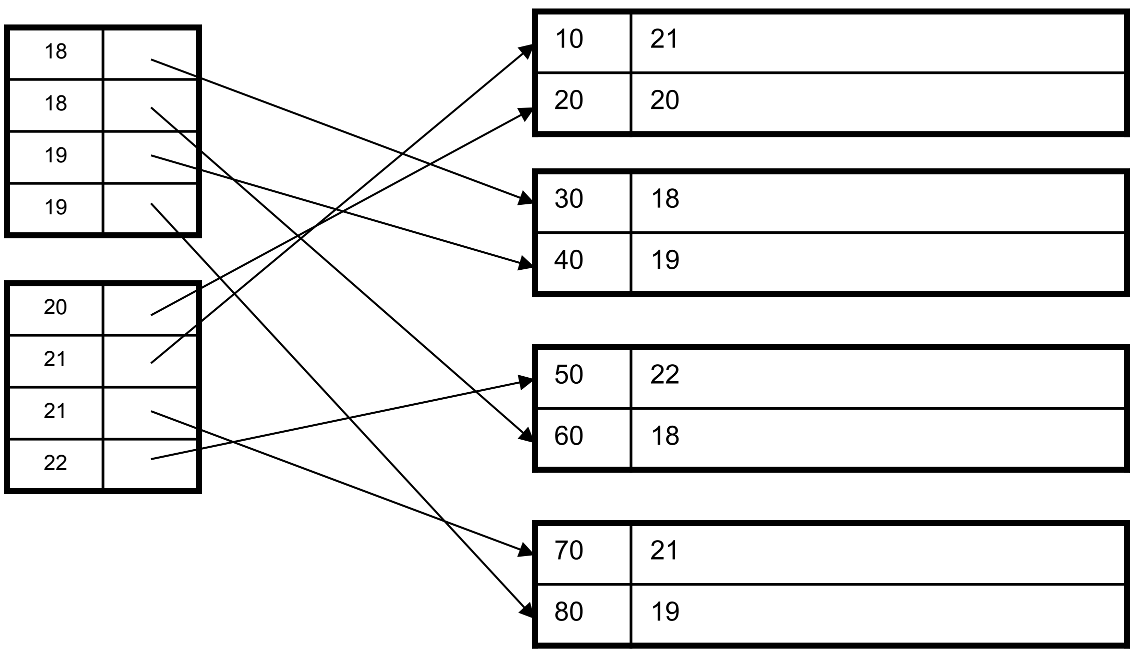


Primary Index: Back to Example

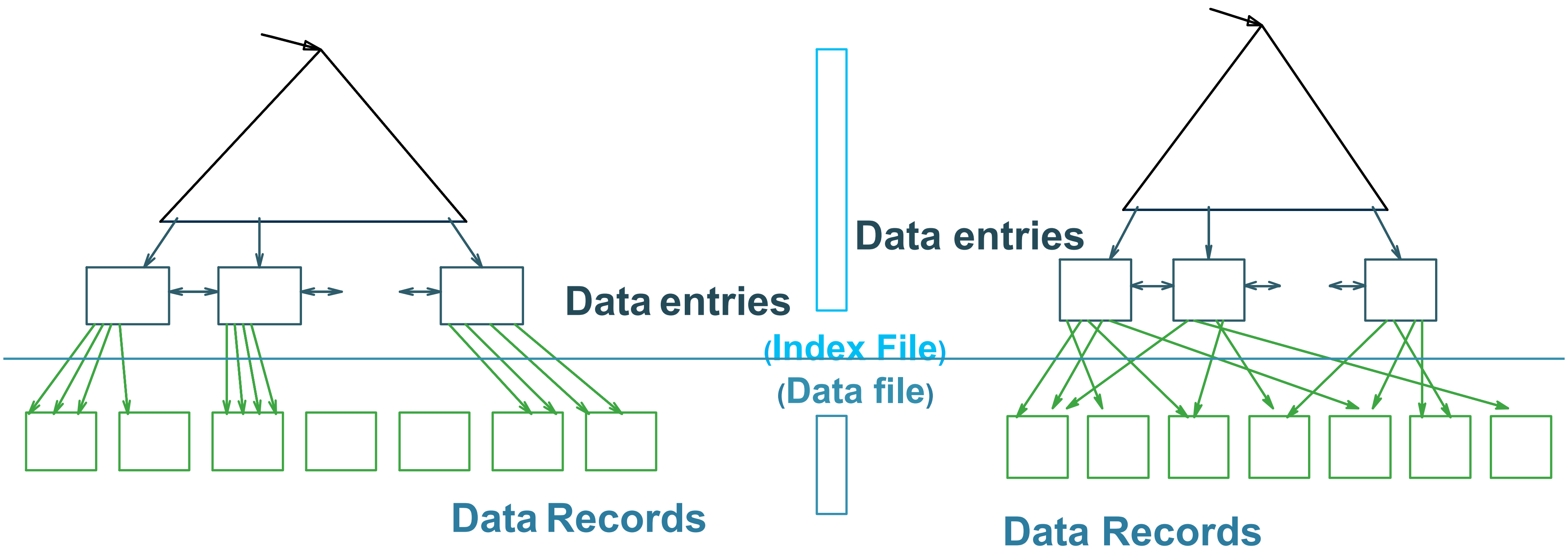
- Let's assume all pages of index fit in memory
- Find student whose sid is 80
  - Index (dense or sparse) points directly to the page
  - Only need to read 1 page from disk.
- Find all students older than 20
  - Must still read all 1,000 pages.
- How can we make *both* queries fast?

Secondary Indexes

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



Clustered vs. Unclustered Index



CLUSTERED **UNCLUSTERED**

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

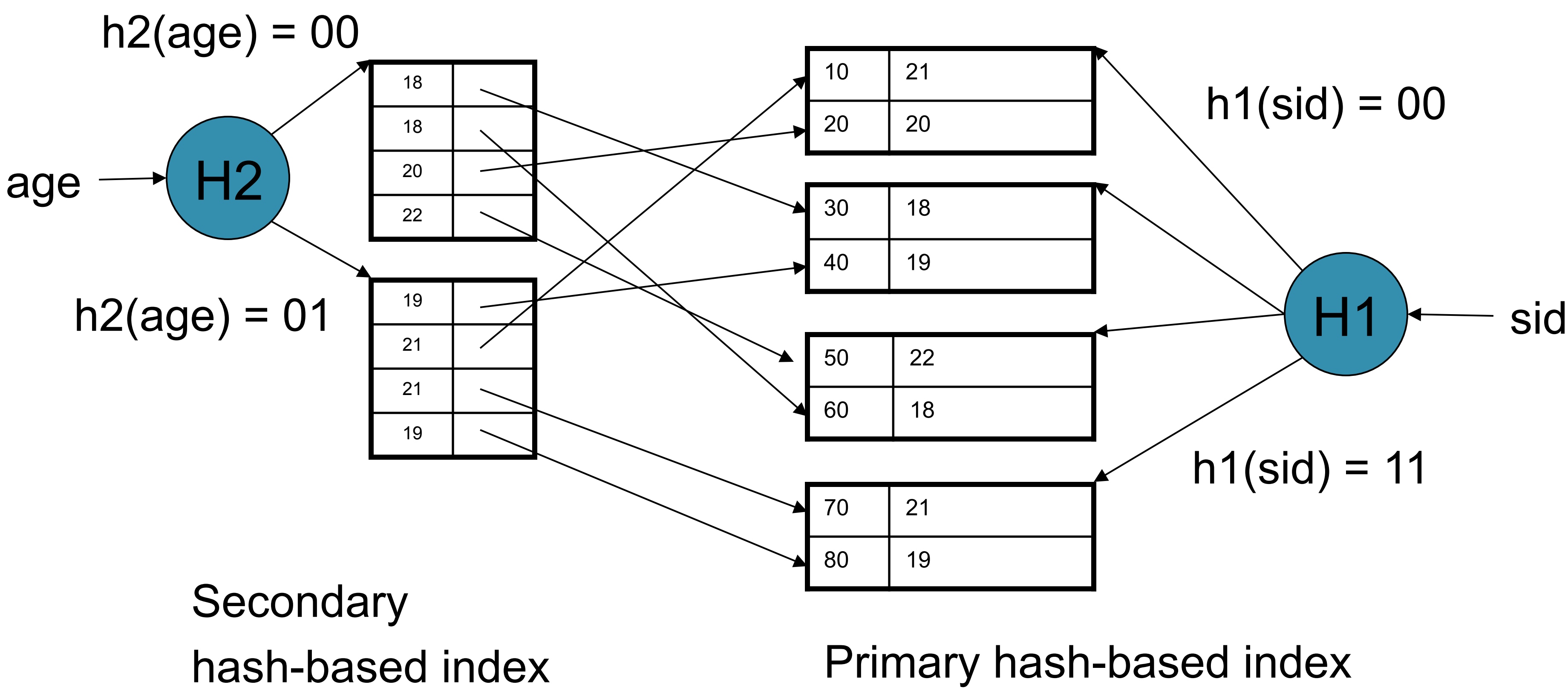
- Primary/secondary
  - Primary = determines the location of indexed records
  - Secondary = cannot reorder data, does not determine data location
- Dense/sparse
  - Dense = every key in the data appears in the index
  - Sparse = the index contains only some keys
- Clustered/unclustered
  - Clustered = 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



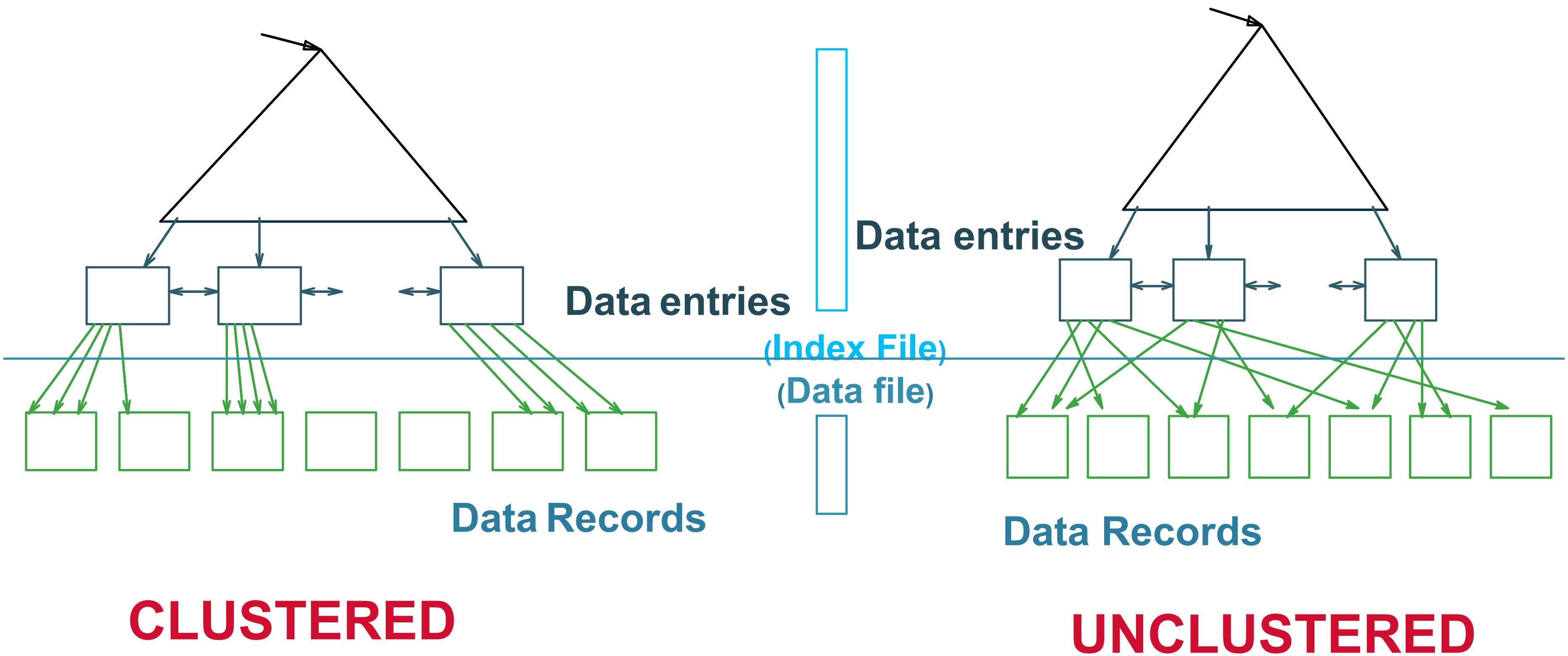
Tree-Based Index

- 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

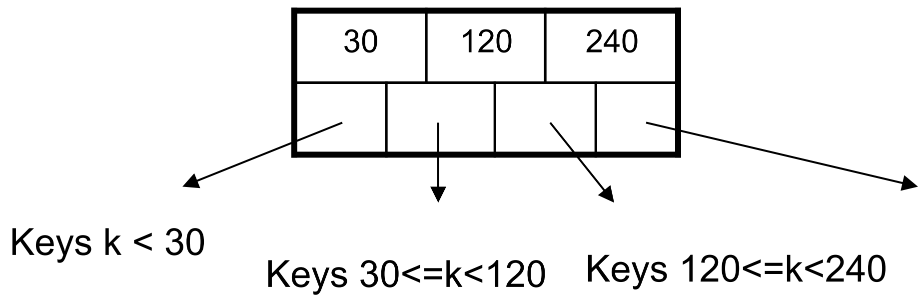
B+ Trees



Note: can also store data records directly as data entries

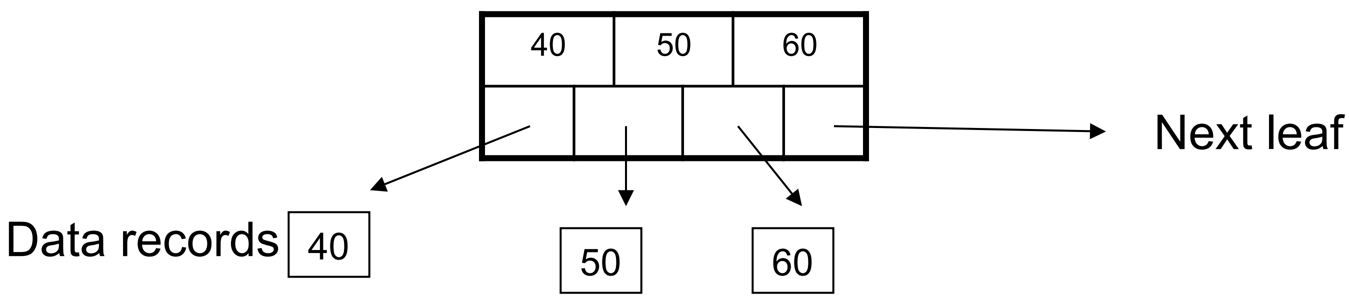
B+ Trees Basics

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



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

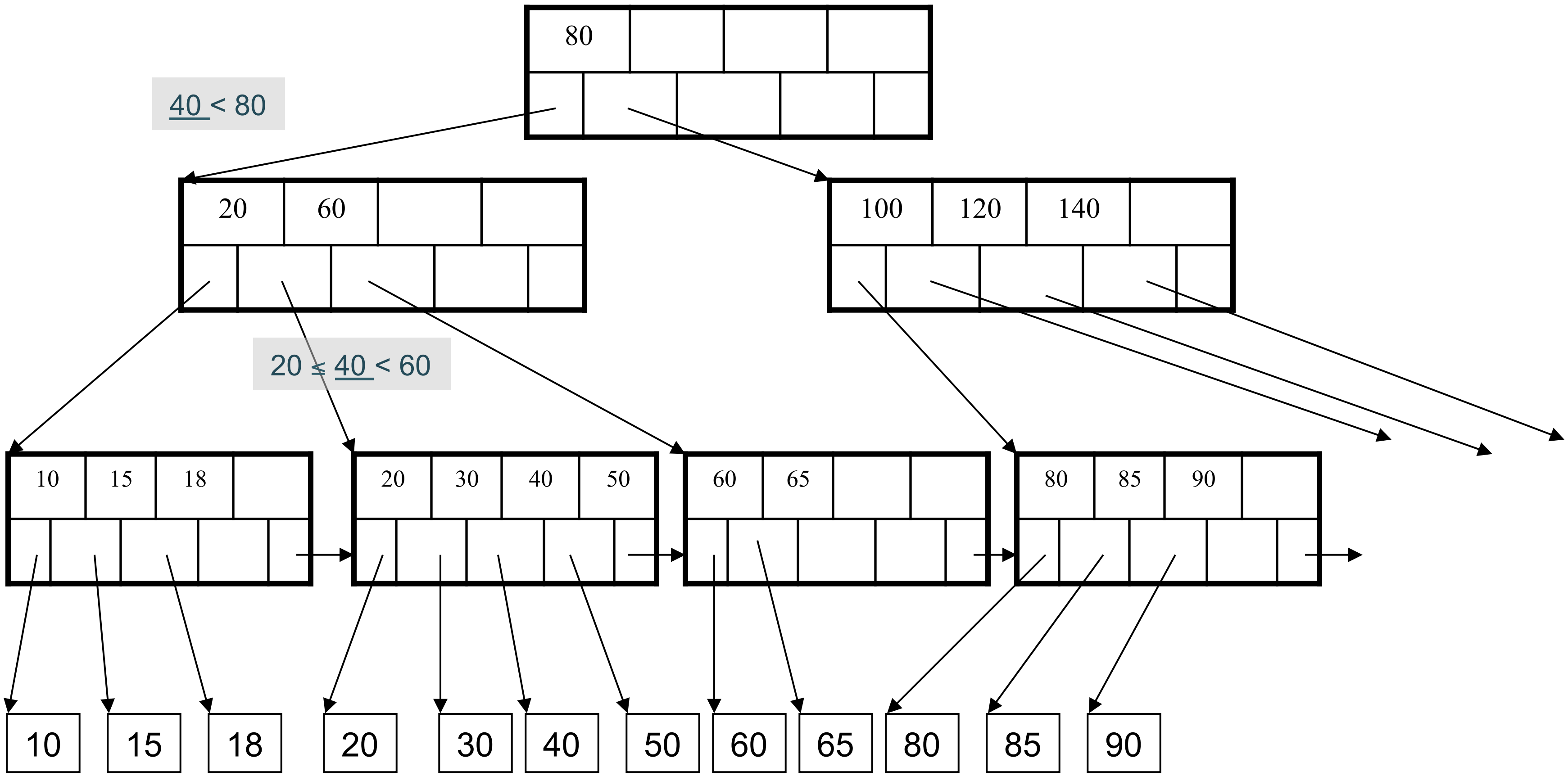
- Each leaf has **d <= m <= 2d keys**:



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

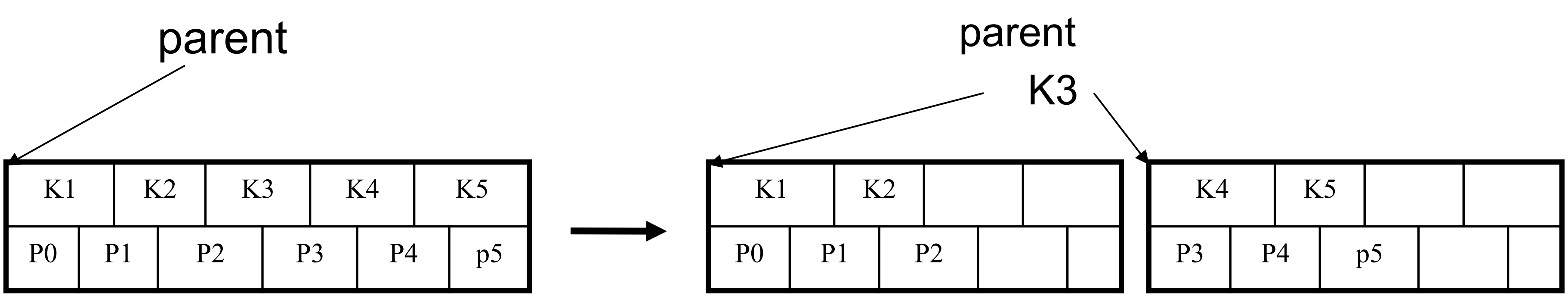
B+ Trees in Practice

- 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)

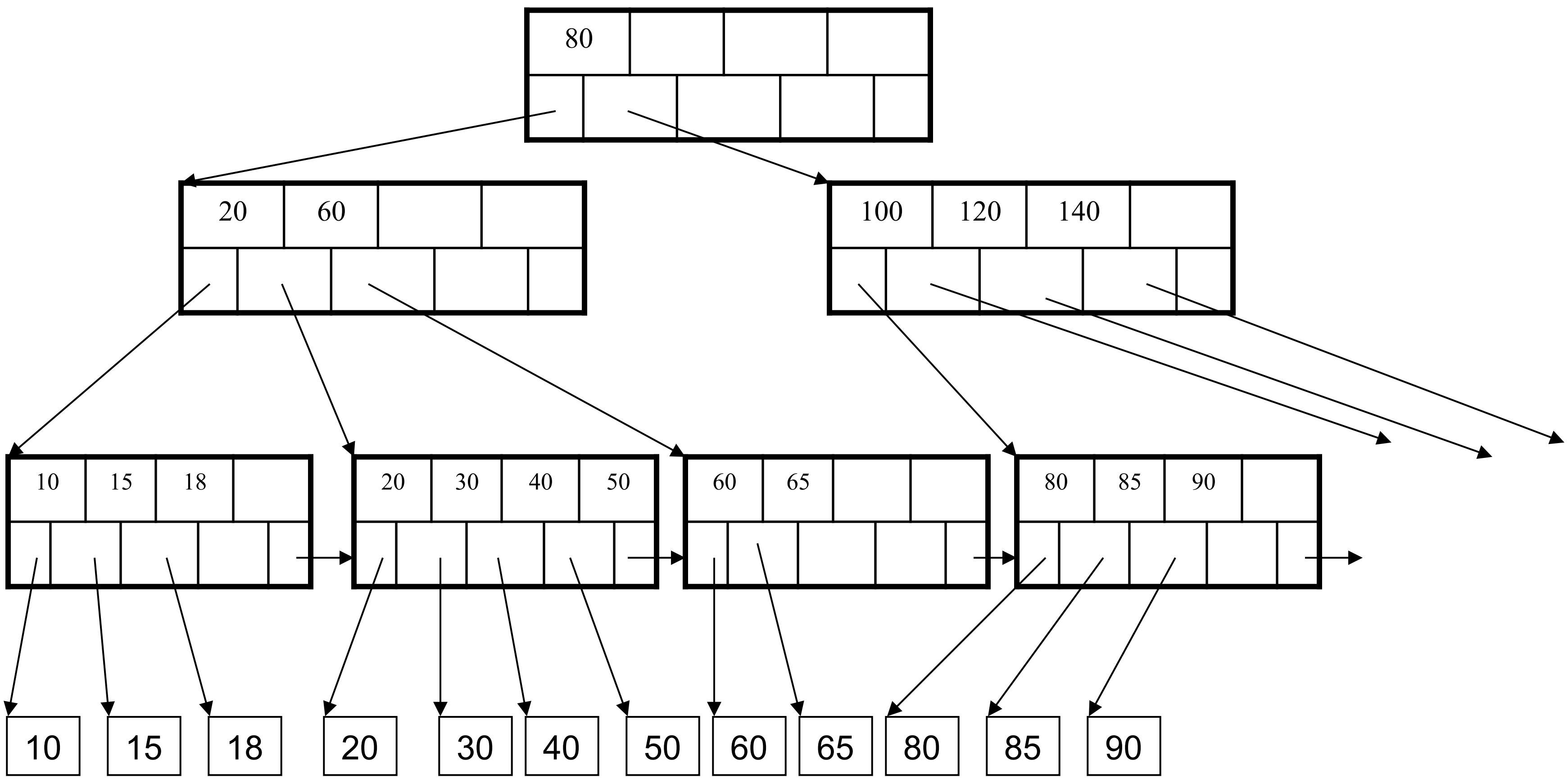
- Find leaf where K belongs, insert
- If no overflow (2d keys or less), halt
- If overflow (2d+1 keys), split node, insert in parent:



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

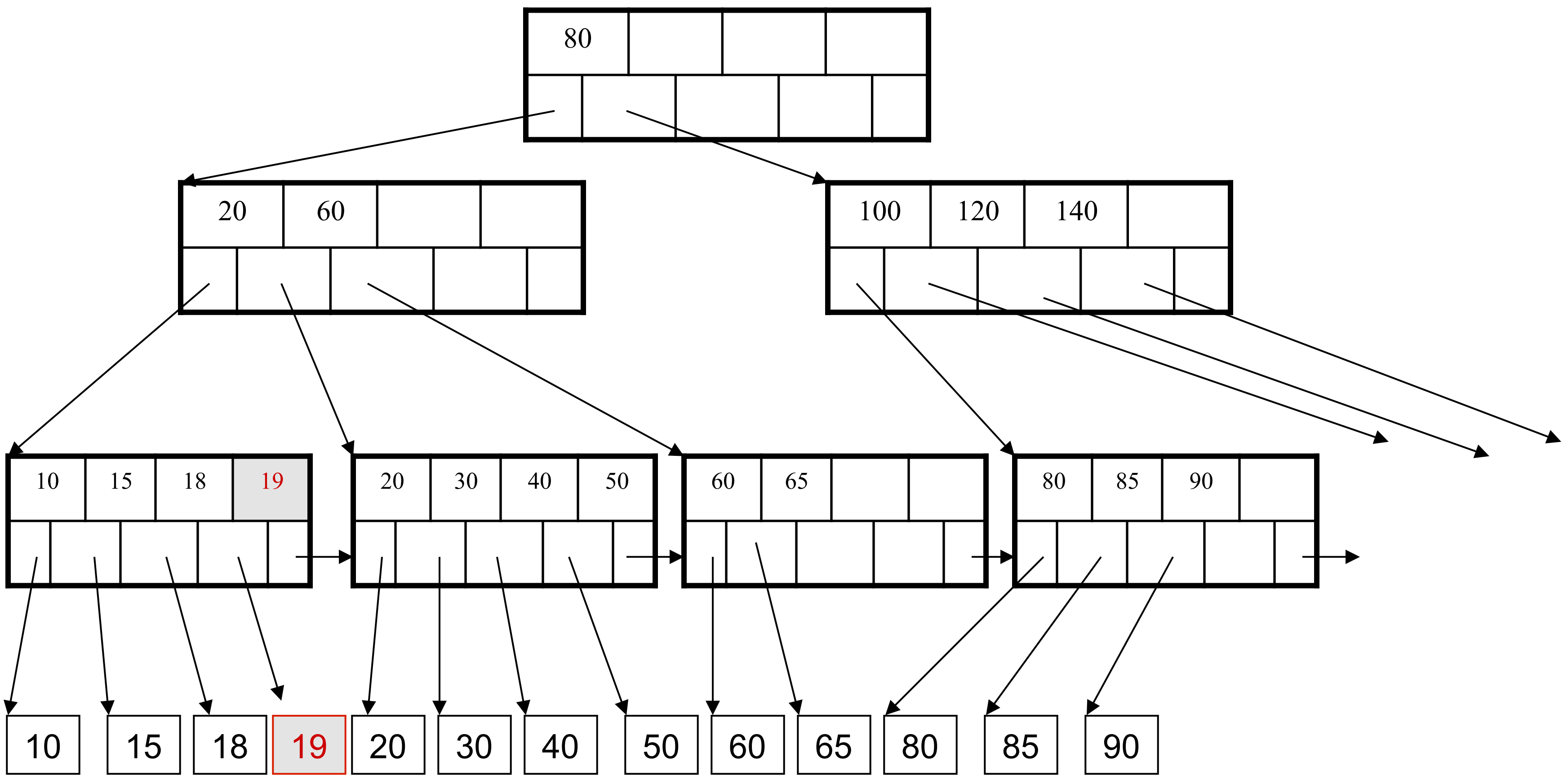
Insertion in a B+ Tree

Insert K=19



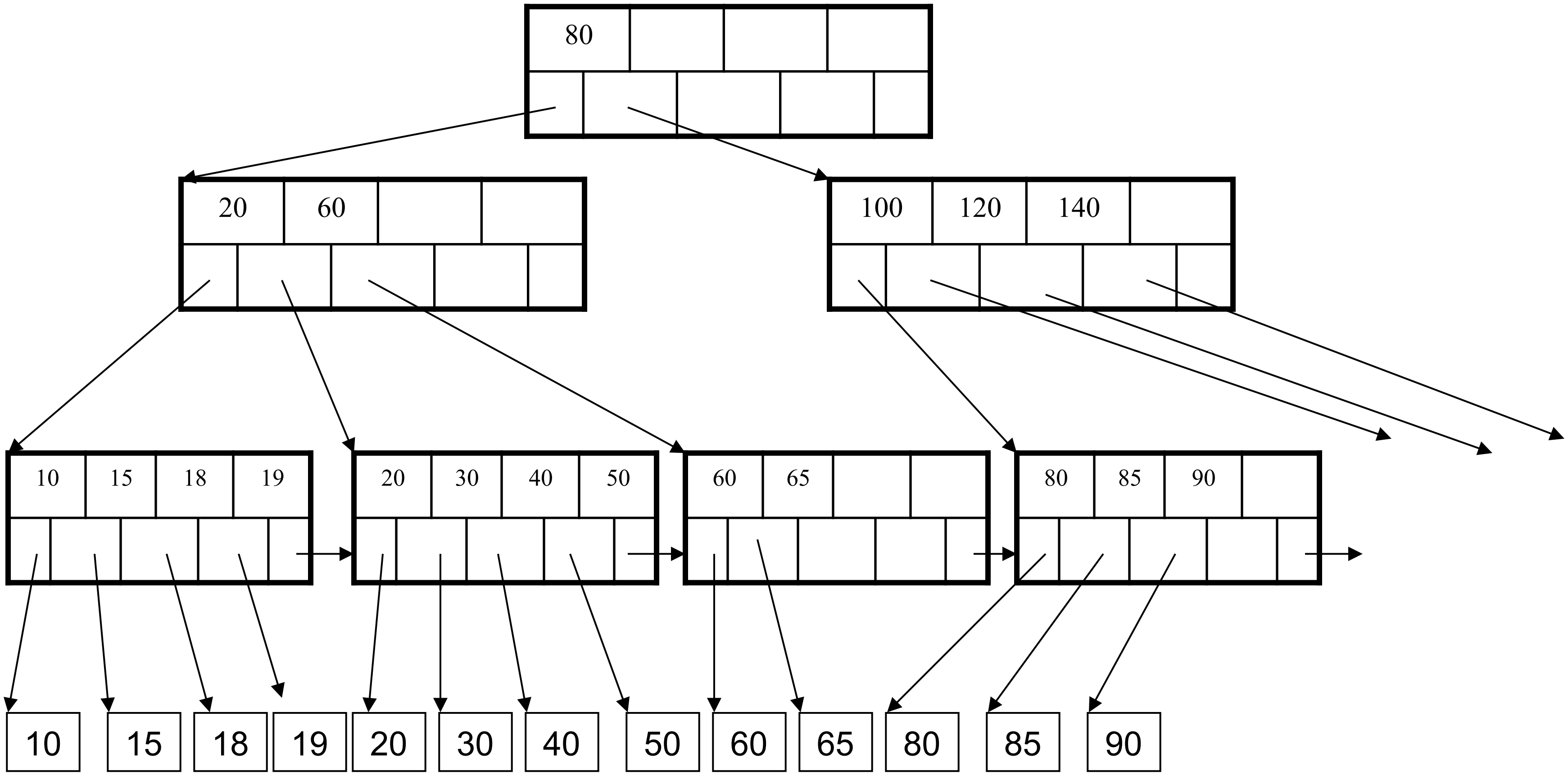
Insertion in a B+ Tree

After insertion



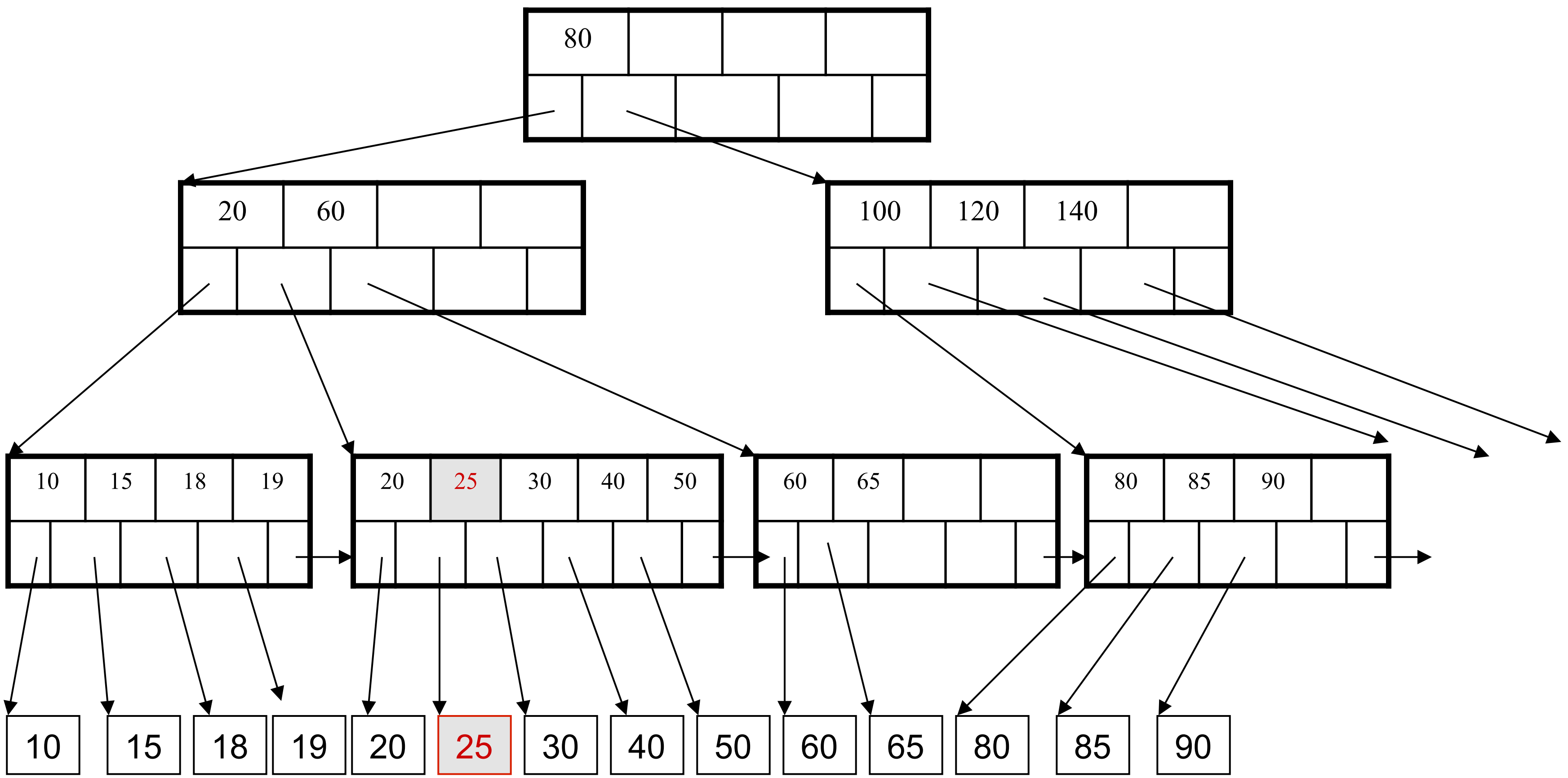
Insertion in a B+ Tree

Now insert 25



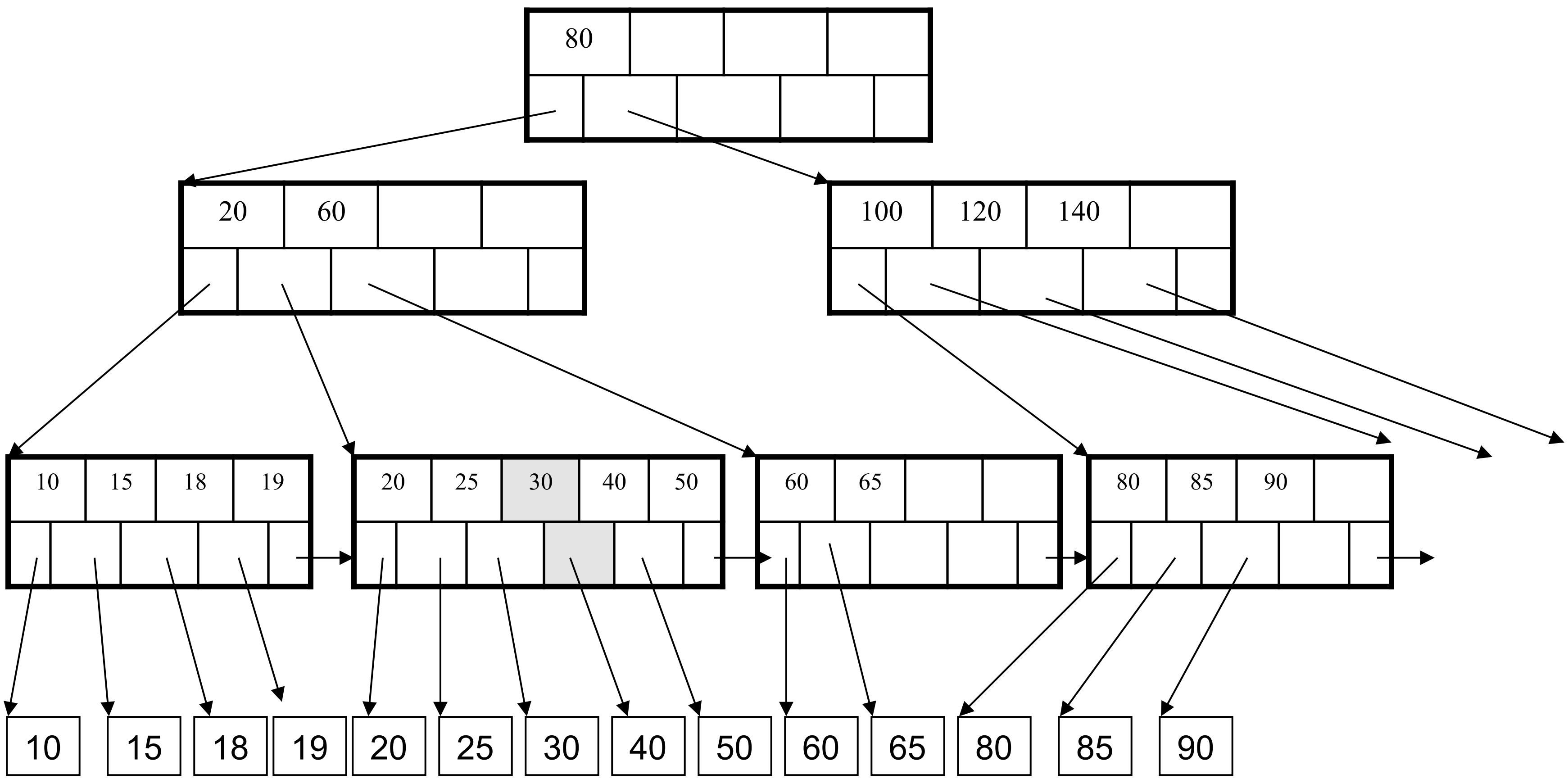
Insertion in a B+ Tree

After insertion



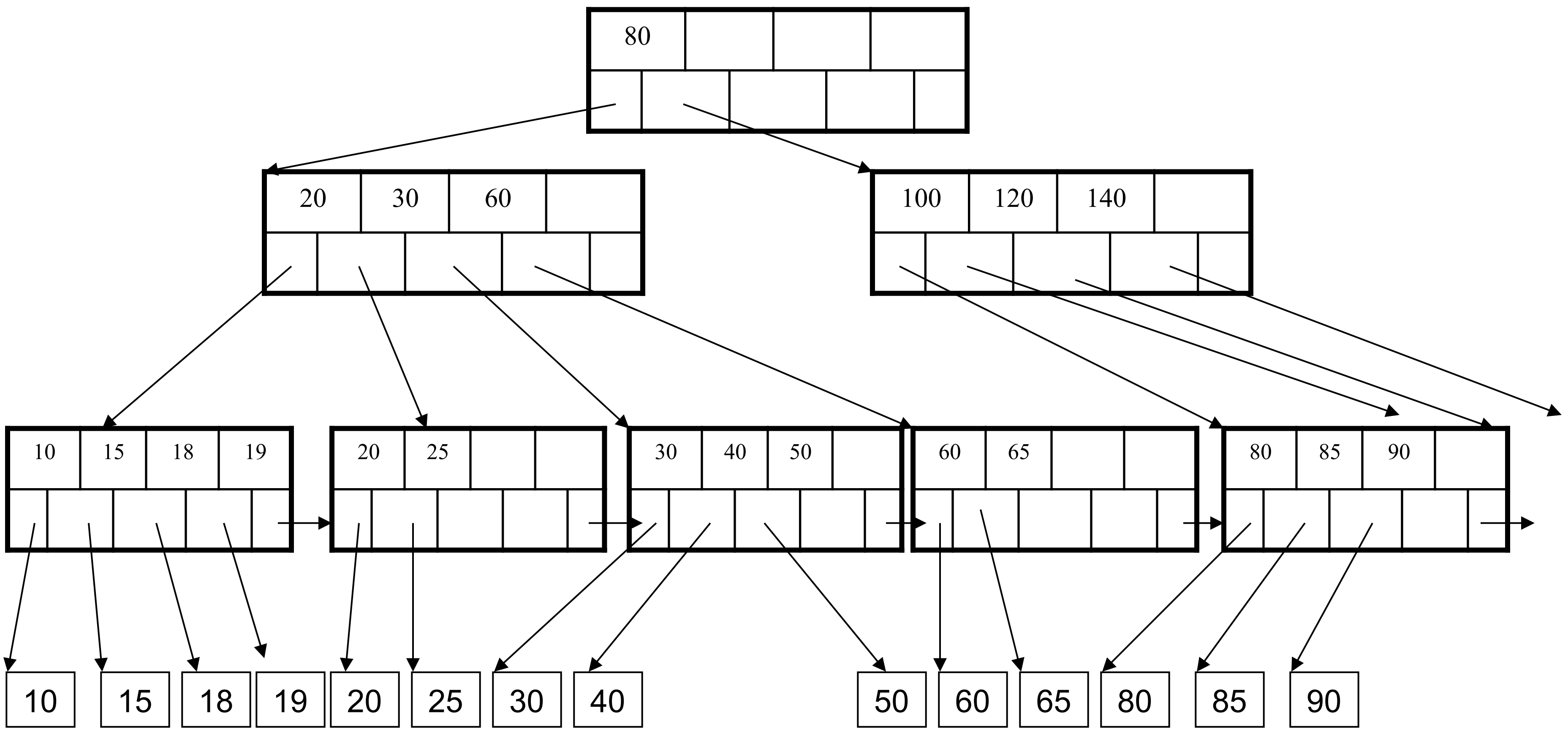
Insertion in a B+ Tree

But now have to split !



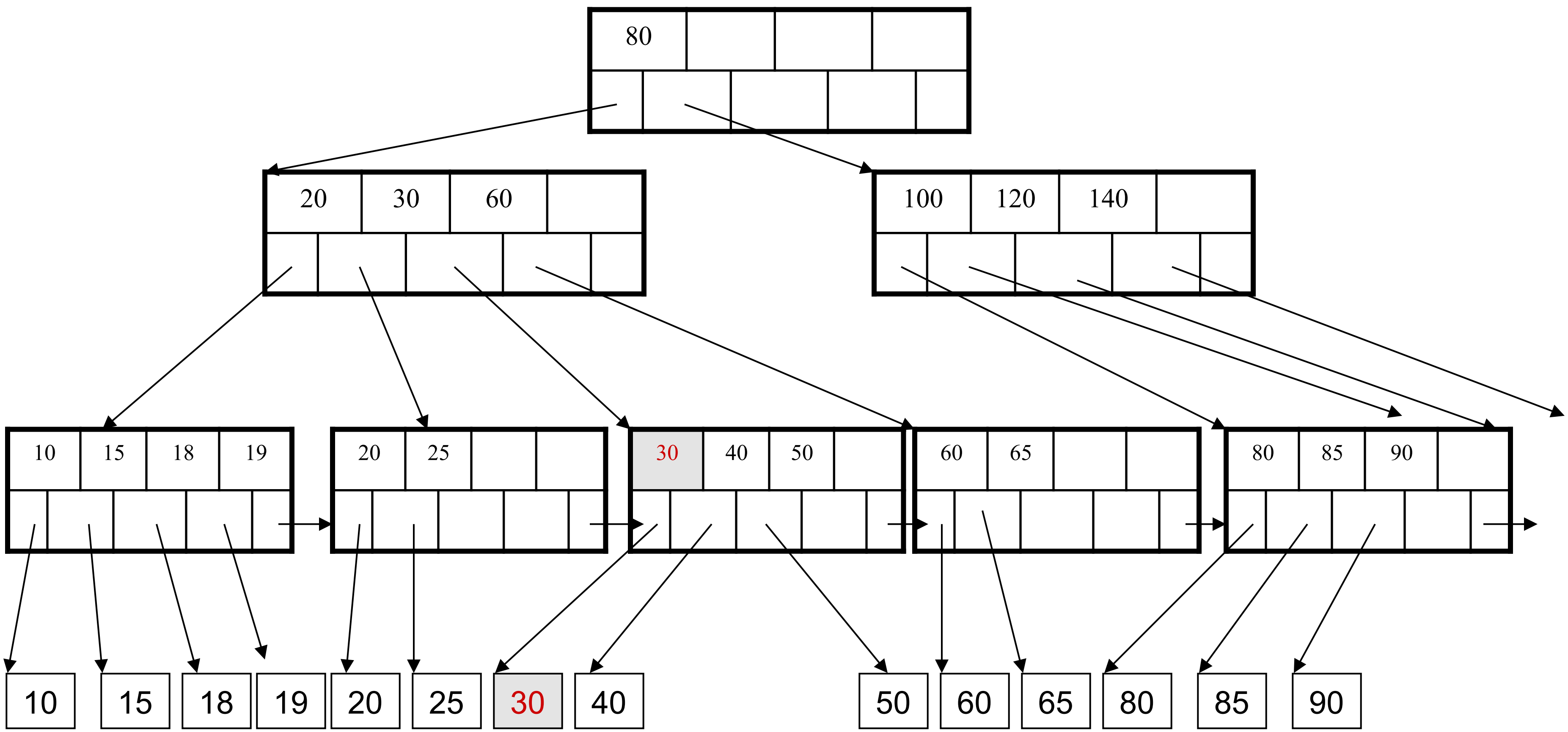
Insertion in a B+ Tree

After the split



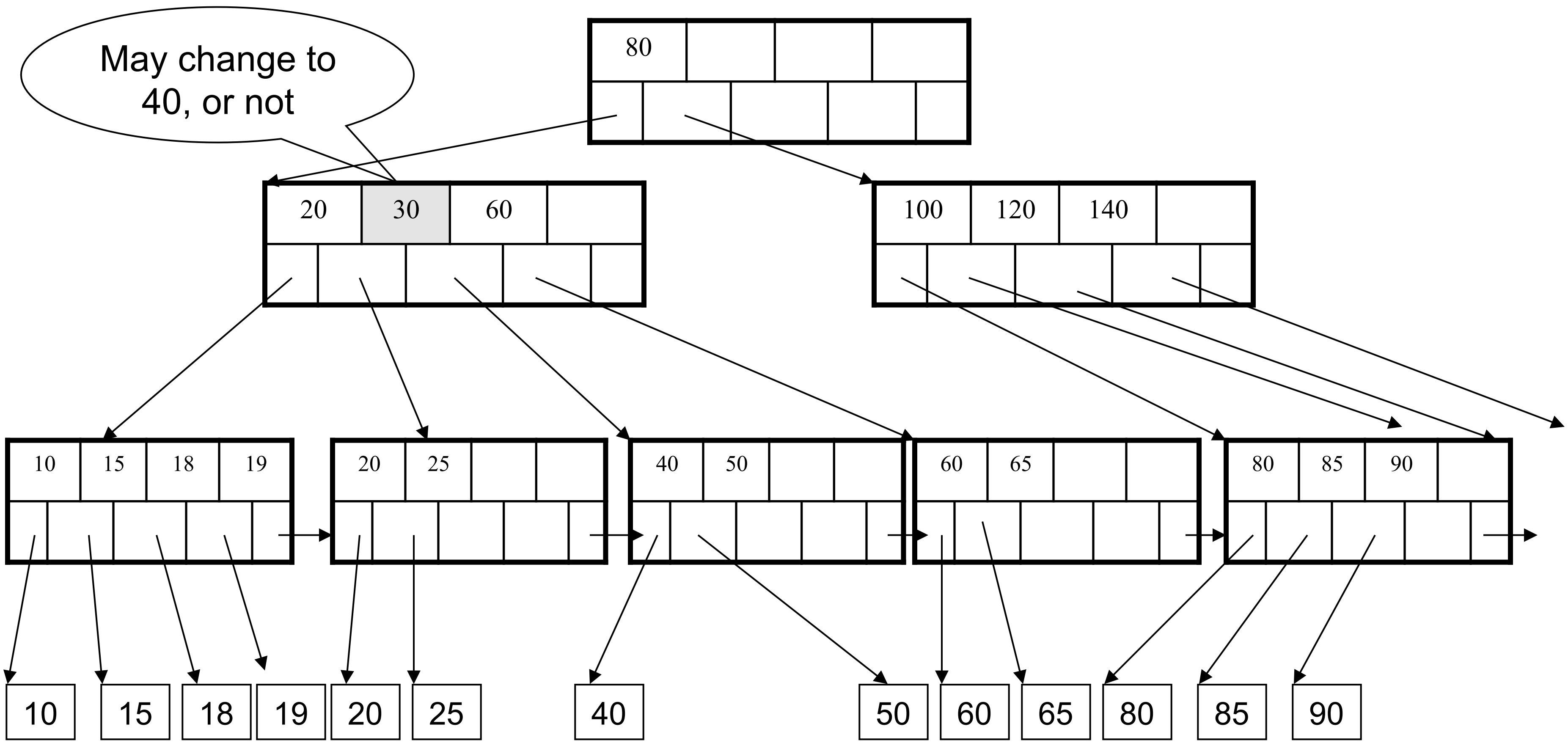
Deletion from a B+ Tree

Delete 30



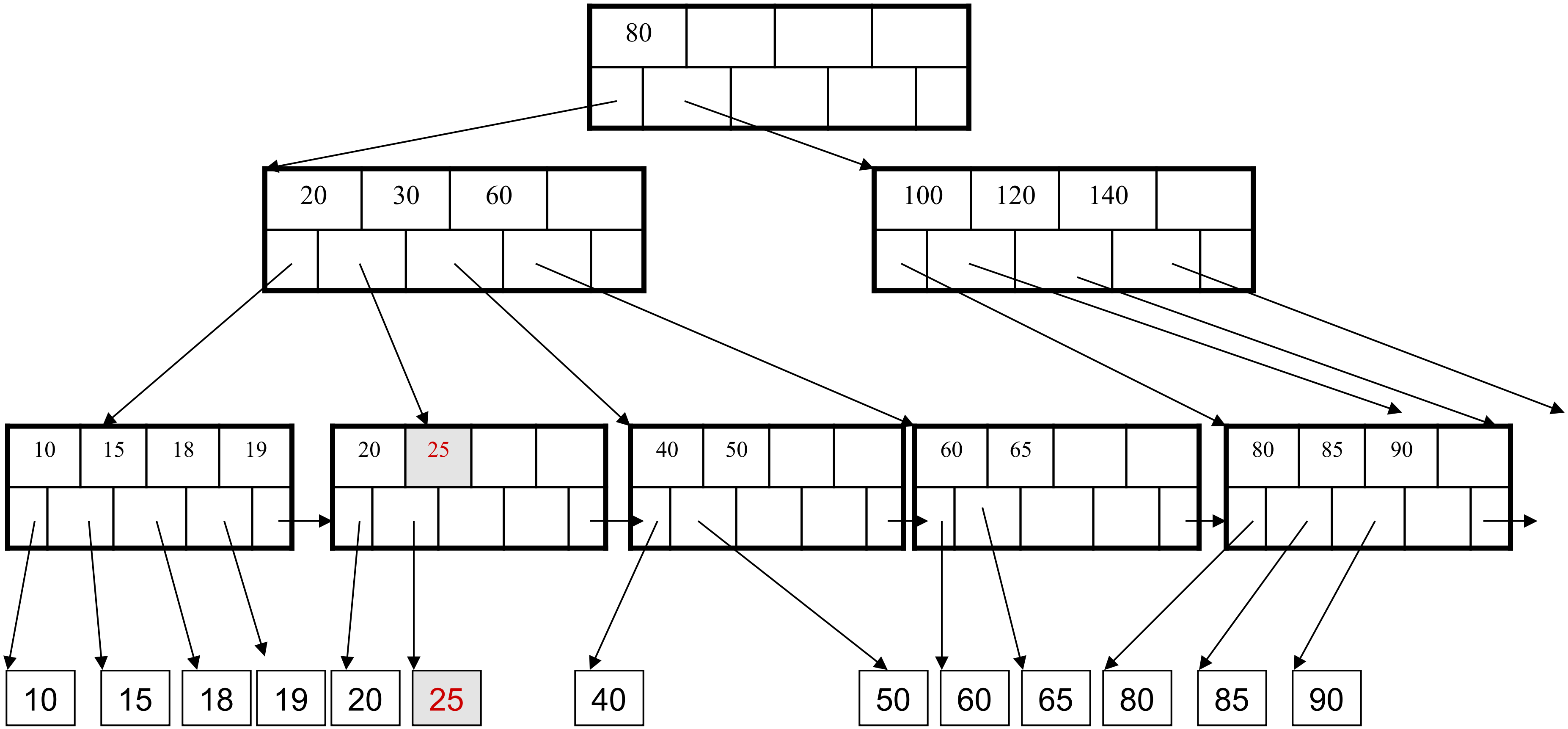
Deletion from a B+ Tree

After deleting 30



Deletion from a B+ Tree

Now delete 25

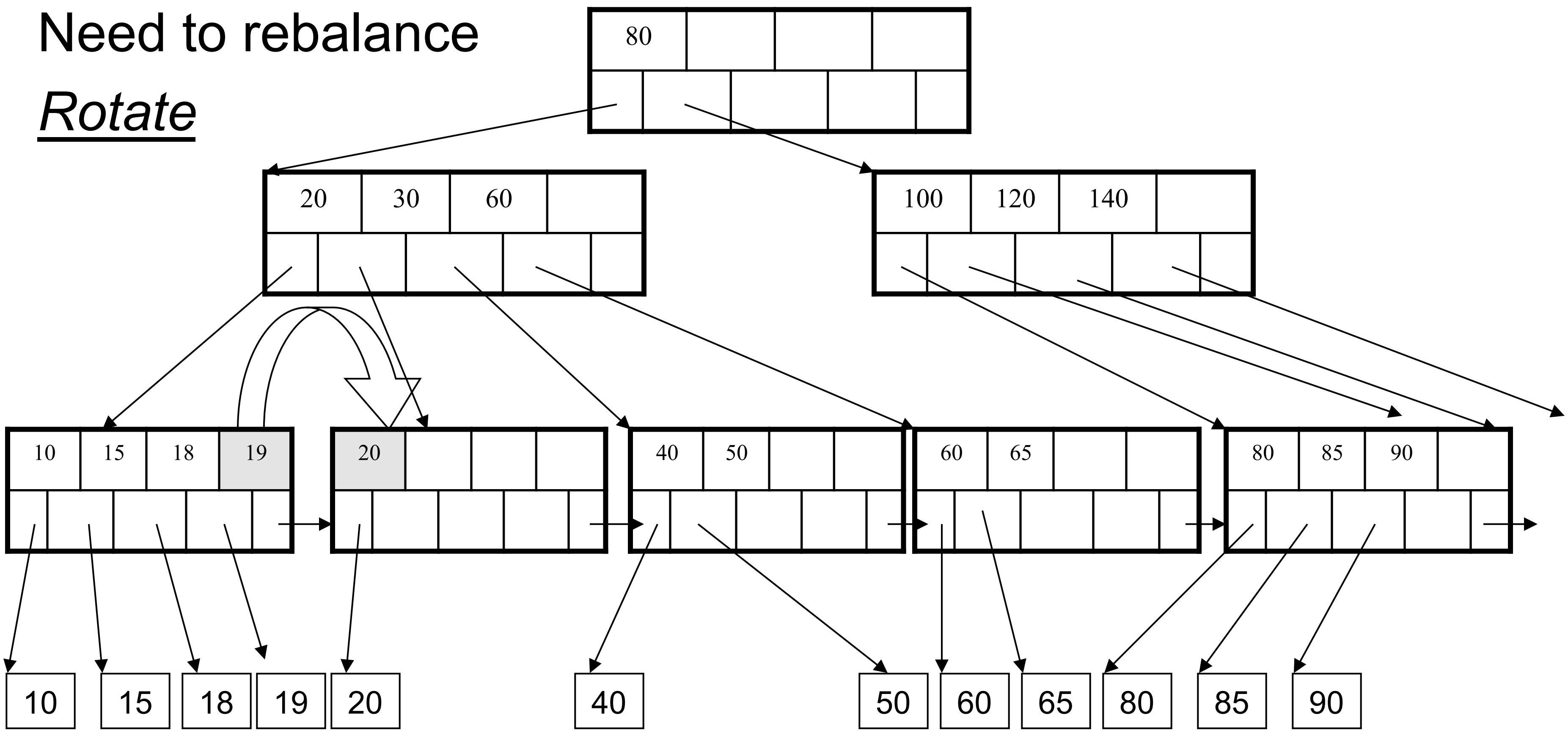


Deletion from a B+ Tree

After deleting 25

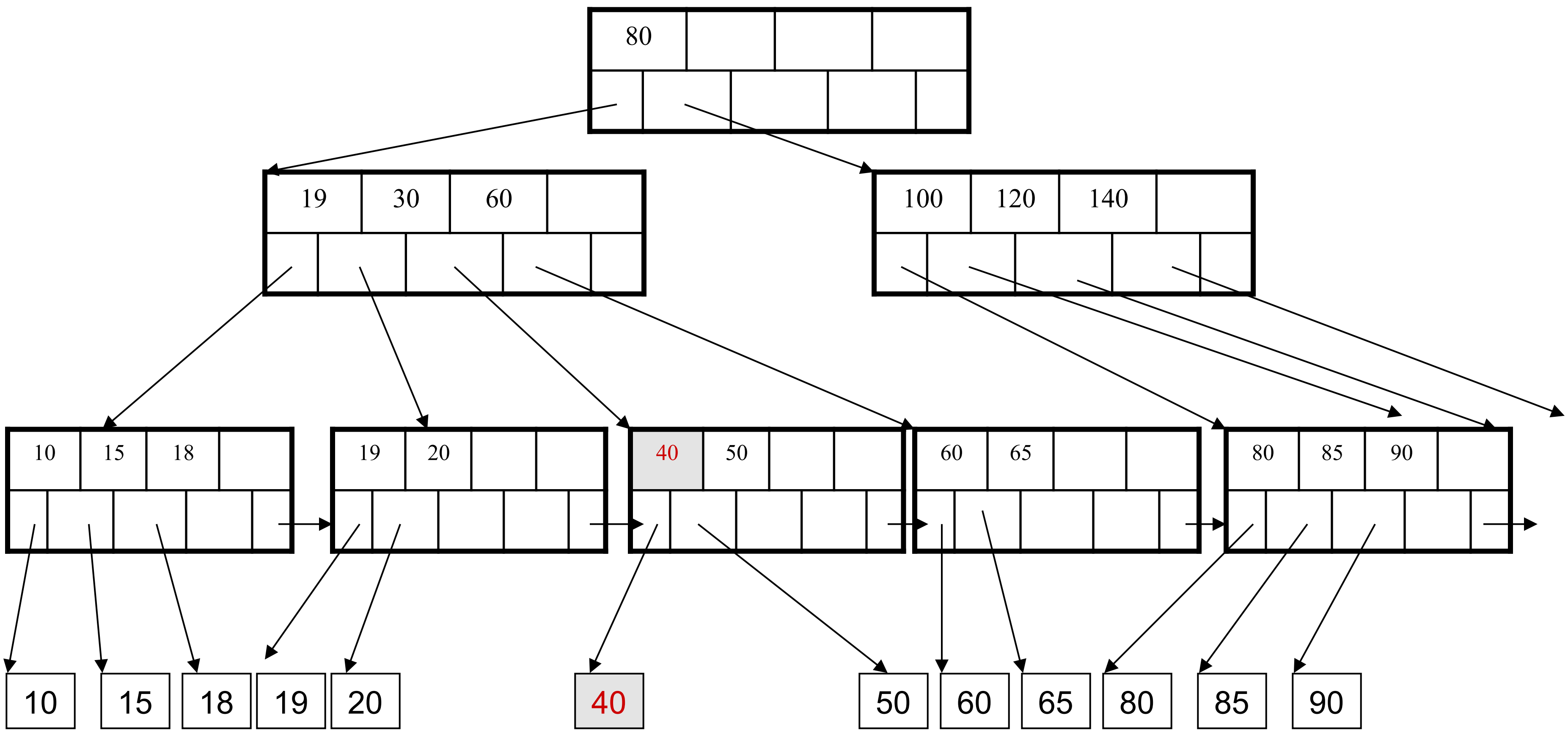
Need to rebalance

<u>*Rotate*</u>



Deletion from a B+ Tree

Now delete 40

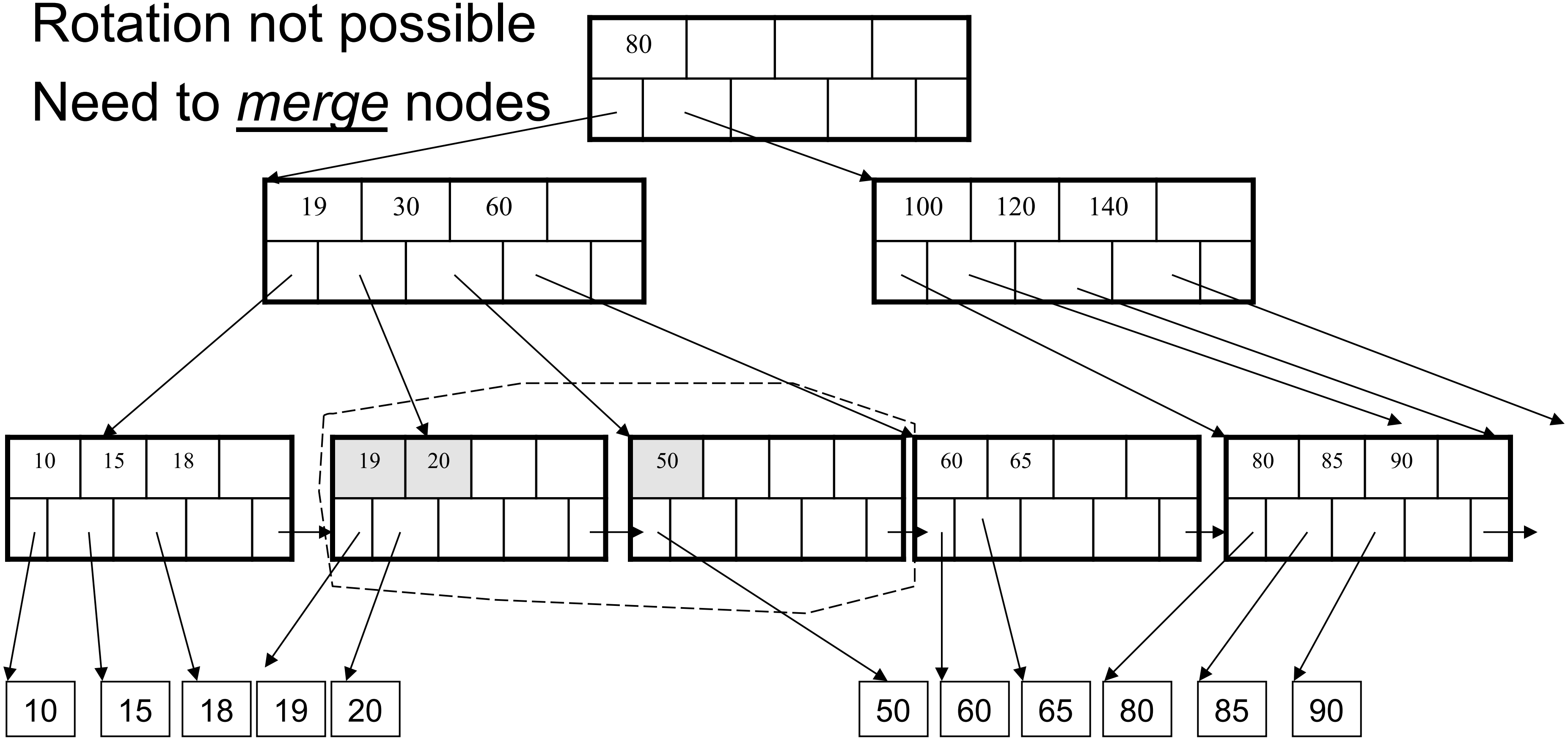


Deletion from a B+ Tree

After deleting 40

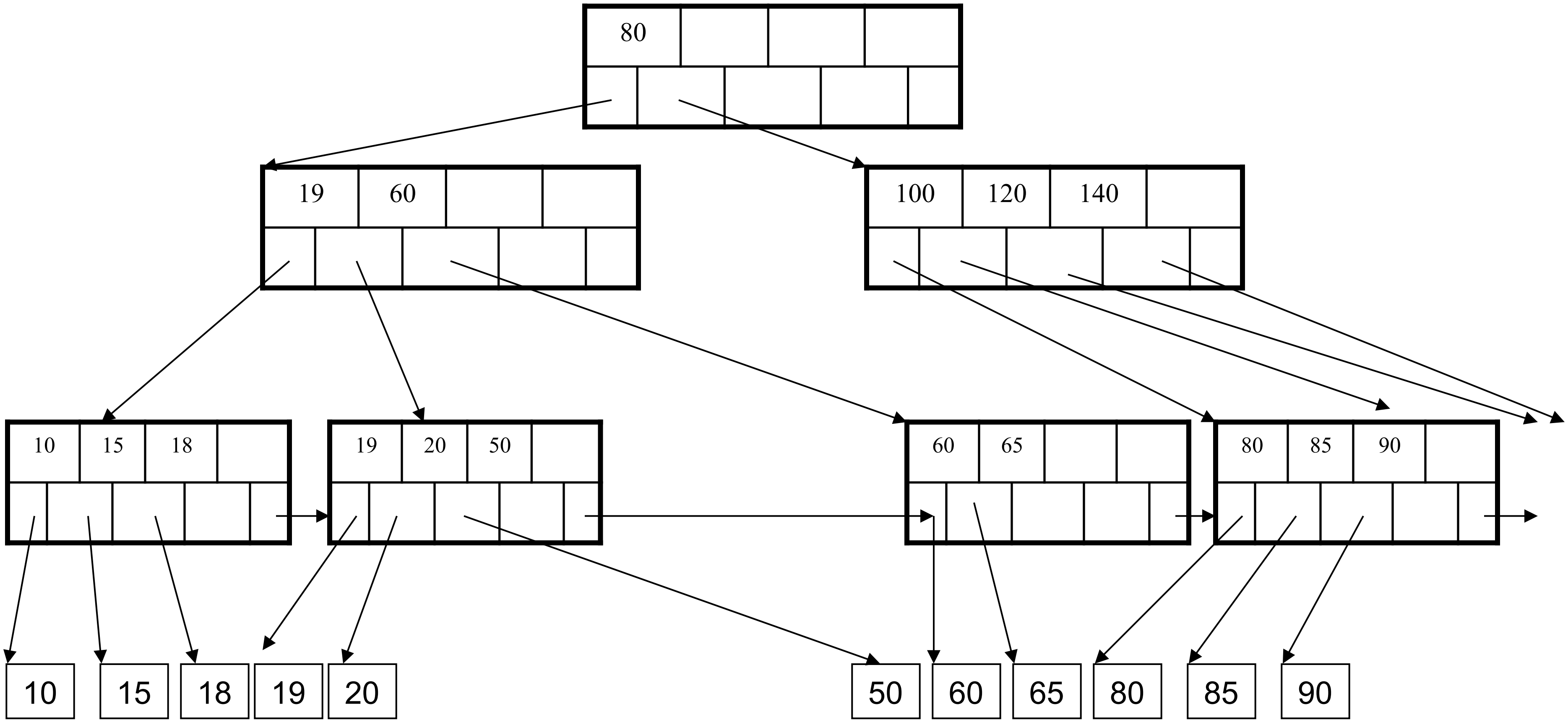
Rotation not possible

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

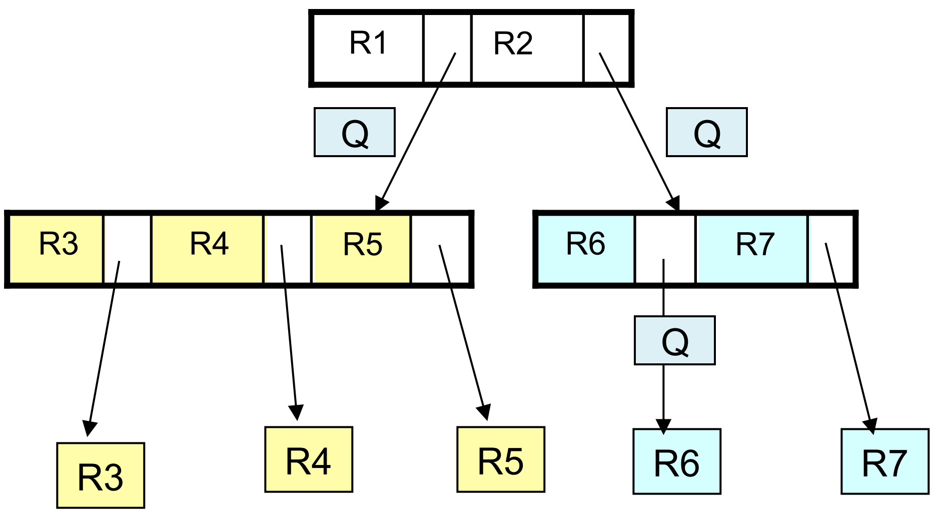
Optional Material

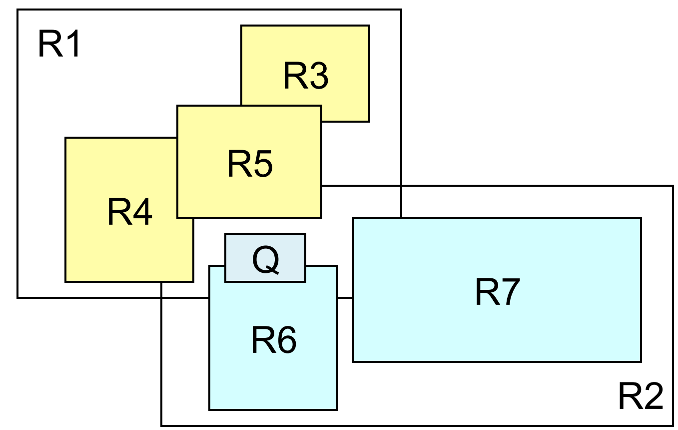
- Let’s take a look at another example of an index….
- The following will not be on the midterm/final

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)