CSE 544
Principles of Database Management Systems

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Fall 2007

Lecture 6 - Storage and Indexing

References

- **Generalized Search Trees for Database Systems**. J. M. Hellerstein, J. F. Naughton and A. Pfeffer. VLDB 1995.

- **Database management systems**. Third Edition. R. Ramakrishnan and J. Gehrke. Chapters 8 through 11

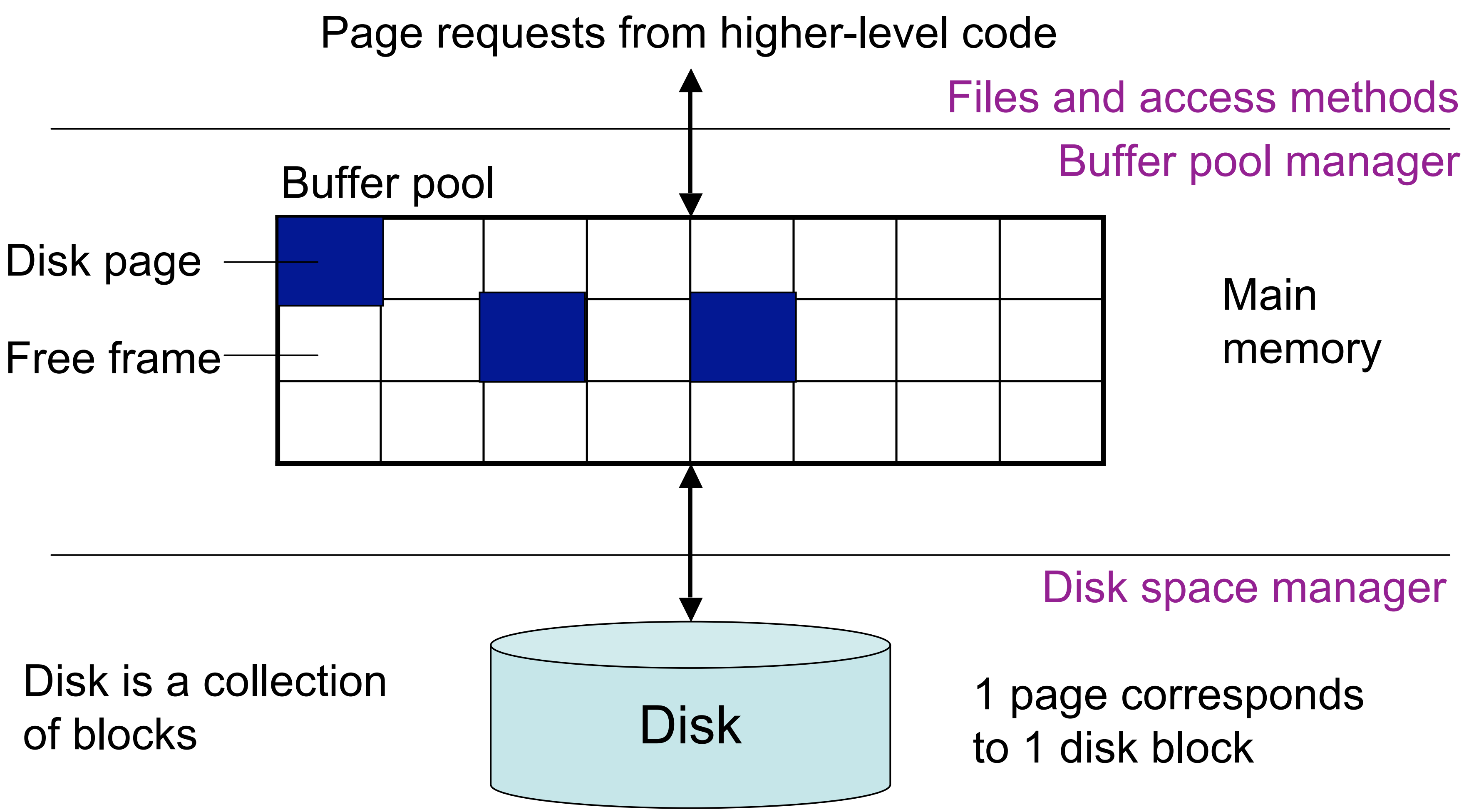
Storage Management

- Can be done by the OS or by the DBMS
- What are the trade-offs? See lecture 5
- How does the DBMS manage storage?

Outline

- **Data storage**
  - Disk and files: Sections 9.3 through 9.7
  - Operations on files
- **Indexes**
  - Index structures: Section 8.3
  - Hash-based indexes: Section 8.3.1 and Chapter 11
  - B+ trees: Section 8.3.2 and Chapter 10
  - GiST: Hellerstein et. al.'s VLDB'95 paper (will finish next lecture)

Buffer Manager



Data Storage

- Basic **abstraction**
  - *Collection of records* *or* *file*
  - Typically, 1 relation = 1 file
  - A file consists of one or more *pages*

- How to organize pages into files?
- How to organize records inside a file?

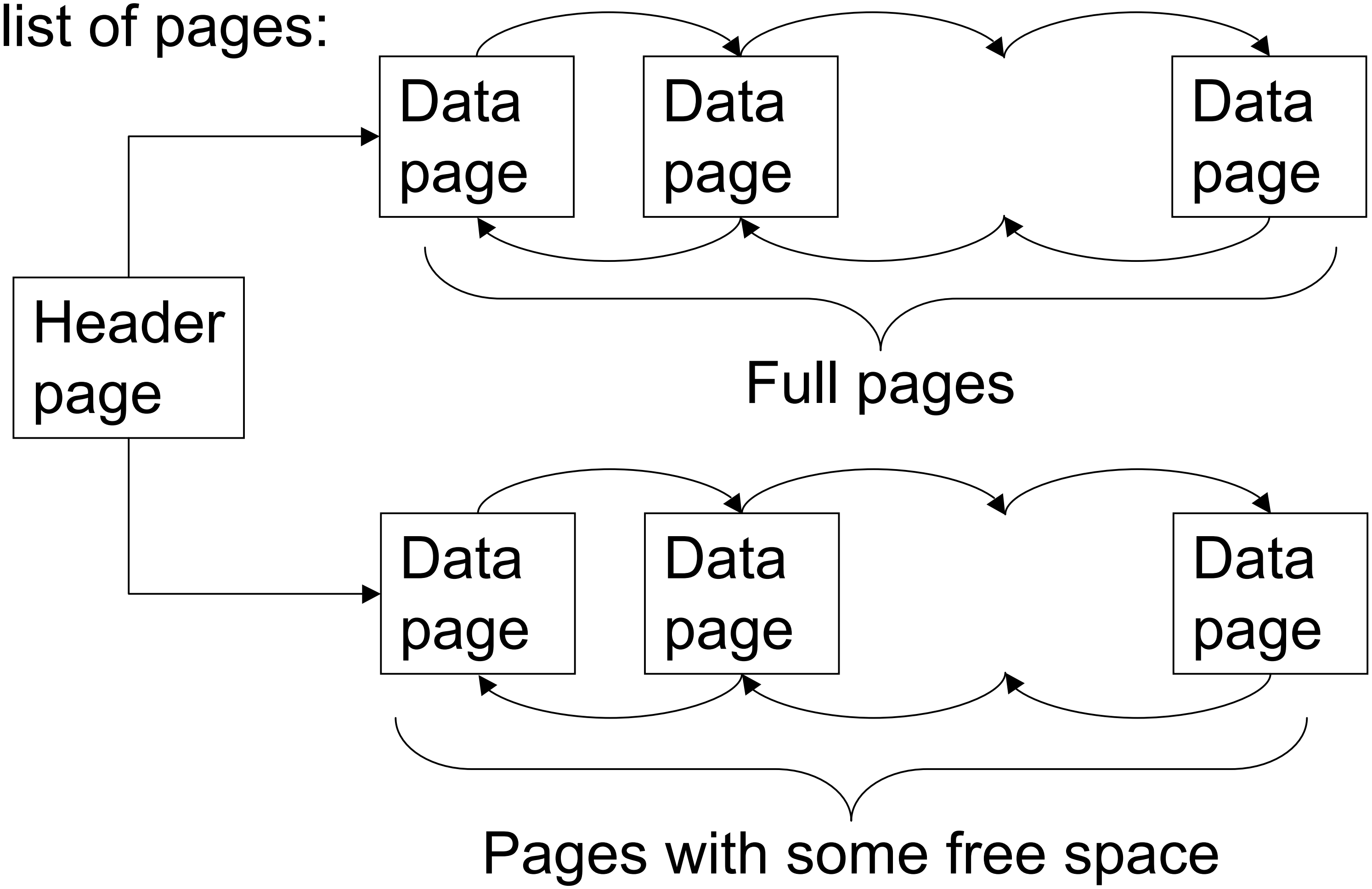
- Simplest approach: **heap file** (unordered)

Heap File Operations

- **Create** or **destroy** a file
- **Insert** a record
- **Delete** a record with a given rid (rid)
  - rid: unique tuple identifier such that
  - can identify disk address of page containing record by using rid
- **Get** a record with a given rid
- **Scan** all records in the file

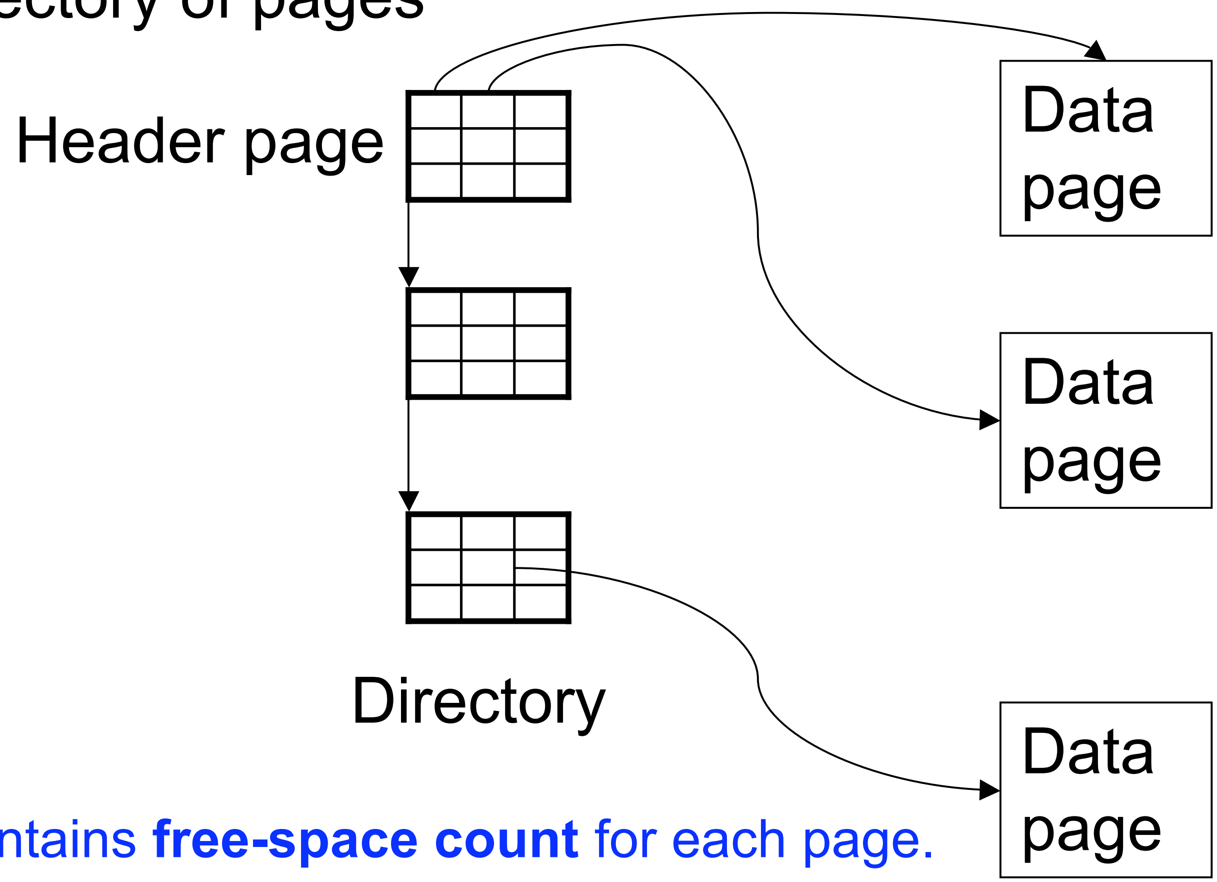
Heap File Implementation 1

Linked list of pages:



Heap File Implementation 2

Better: directory of pages



Directory contains **free-space count** for each page.
Faster inserts for variable-length records

Page Formats

Issues to consider

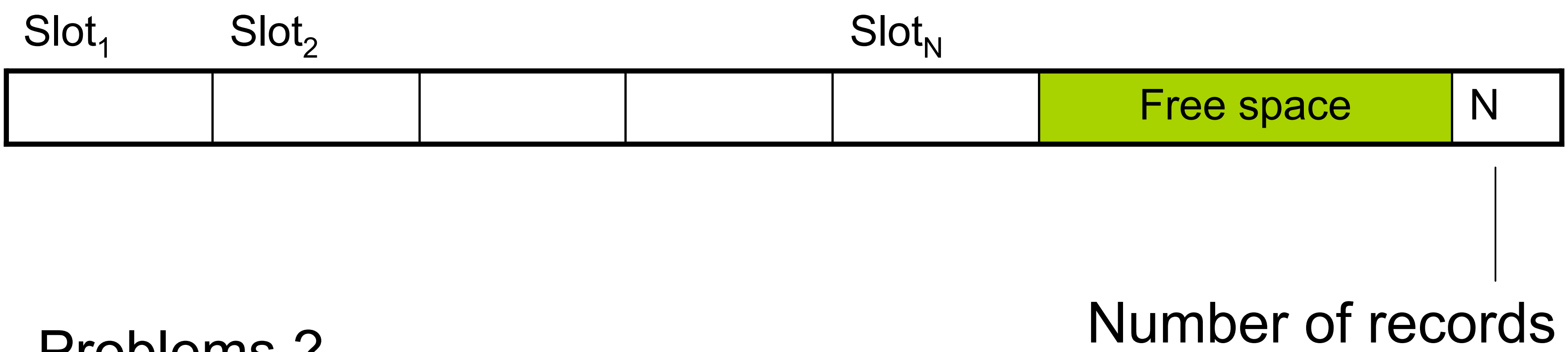
- 1 page = 1 disk block = fixed size (e.g. 8KB)
- Records:
  - Fixed length
  - Variable length
- Record id = RID
  - Typically RID = (PageID, SlotNumber)

Why do we need RID’s in a relational DBMS ?

See discussion about indexes later in the lecture

Page Format Approach 1

Fixed-length records: packed representation

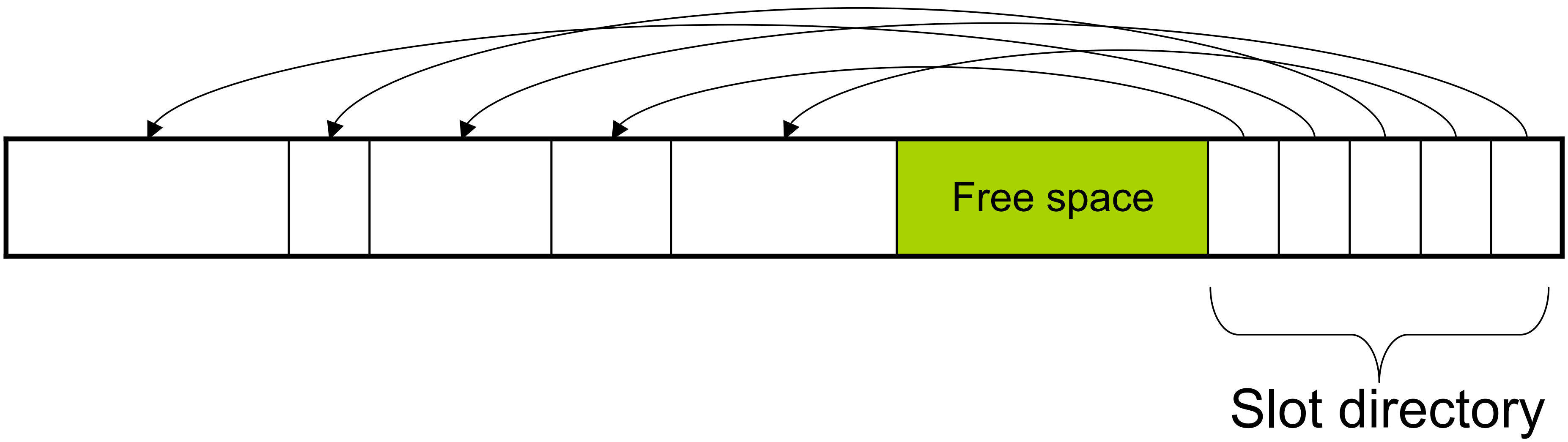


Problems ?

How to handle variable-length records?

Need to move records for each deletion, changing RIDs

Page Format Approach 2



Each slot contains
<record offset, record length>

Can handle variable-length records
Can move tuples inside a page without changing RIDs

Record Formats

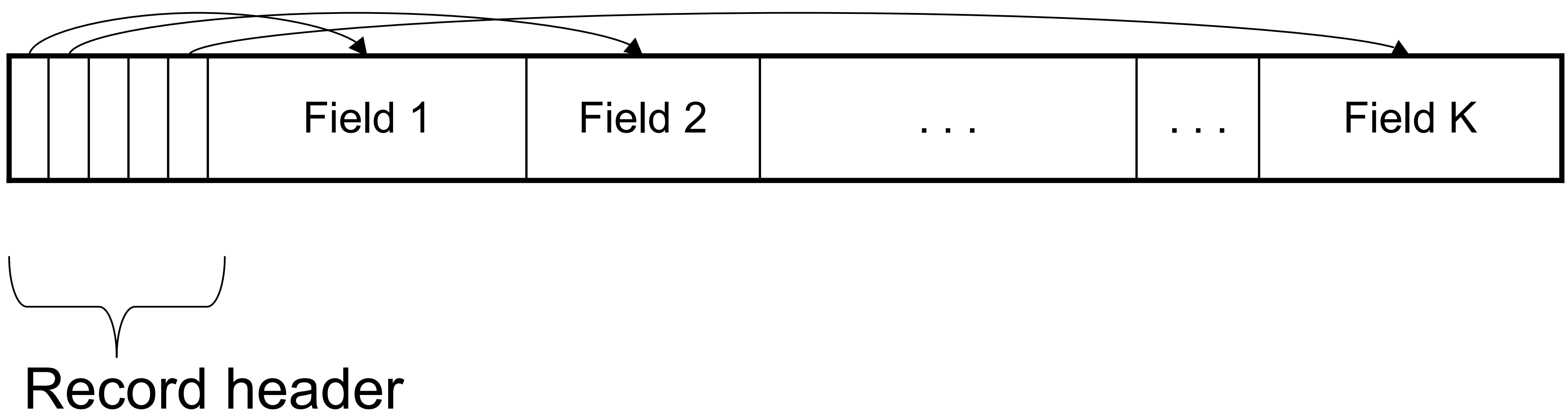
Fixed-length records → Each field has a fixed length (i.e., it has the same length in all the records)

Field 1	Field 2	. . .	. . .	Field K

Information about field lengths and types is in the catalog

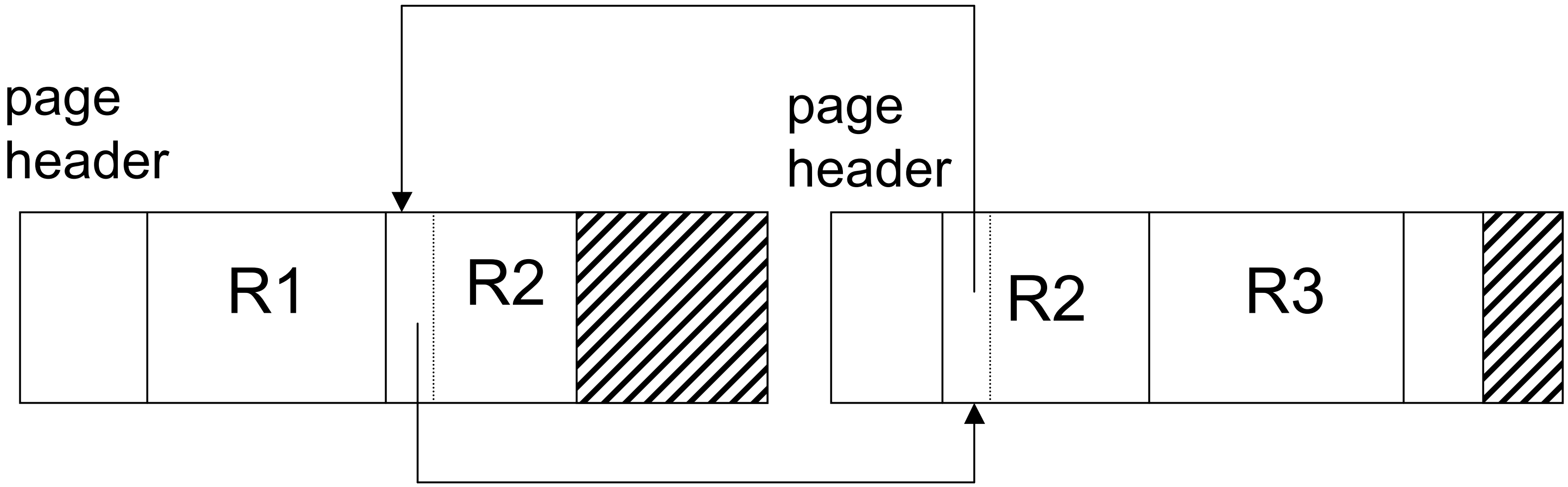
Record Formats

Variable length records



Remark: NULLS require no space at all (why ?)

Long Records Across Pages



- When records are very large
- Or even medium size: saves space in blocks
- Commercial RDBMSs avoid this

LOB

- Large objects
  - Binary large object: BLOB
  - Character large object: CLOB

- Supported by modern database systems
- E.g. images, sounds, texts, etc.

- Storage: attempt to cluster blocks together

Types of Files

- **Heap file**
  - Unordered
- **Sorted file (also called sequential file)**
- **Clustered file**

We discussed heap files

The others are similar

Outline

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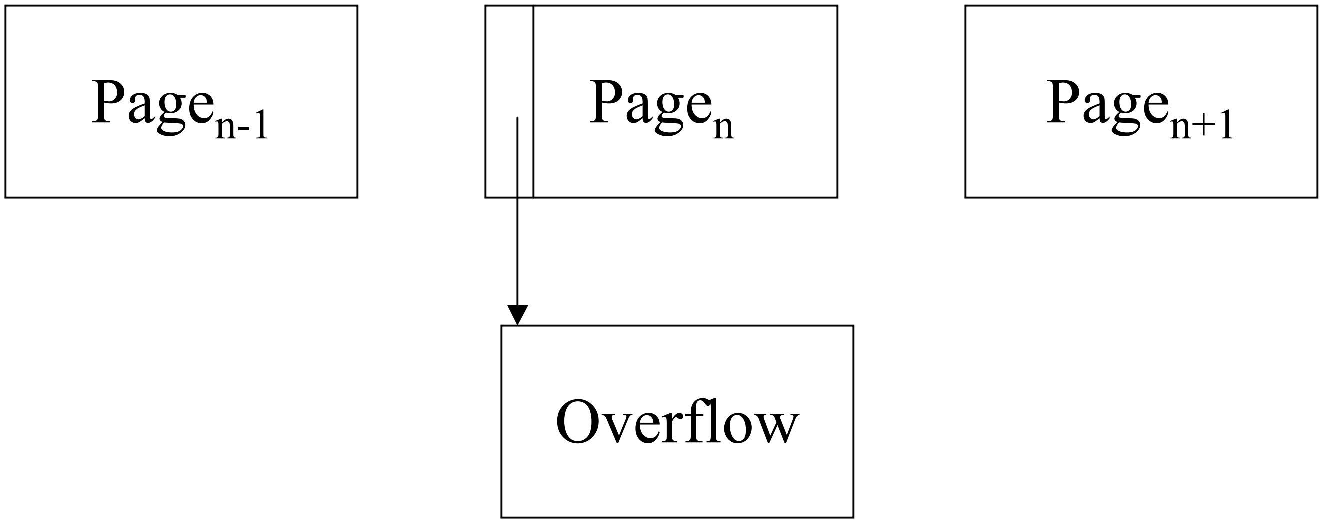
  - Index structures: Section 8.3
  - Hash-based indexes: Section 8.3.1
  - B+ trees: Chapter 10

Modifications: Insertion

- File is unsorted (= ***heap file***)
  - add it wherever there is space (easy ☺)
- File is sorted
  - Is there space on the right page ?
    - Yes: we are lucky, store it there
  - Is there space in a neighboring page ?
    - Look 1-2 pages to the left/right, shift records
  - If anything else fails, create ***overflow page***

Overflow Pages



- After a while the file starts being dominated by overflow pages: time to reorganize

Modifications: Deletions

- Free space in page, shift records
  - Be careful with slots
  - RIDs for remaining tuples must NOT change
- May be able to eliminate an overflow page

Modifications: Updates

- If new record is shorter than previous, easy ☺
- If it is longer, need to shift records
  - May have to create overflow pages

Searching in a Heap File

File is not sorted on any attribute

`Student(sid: int, age: int, …)`

30	18 …
70	21

1 record

20	20
40	19

1 page

80	19
60	18

10	21
50	22

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?

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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

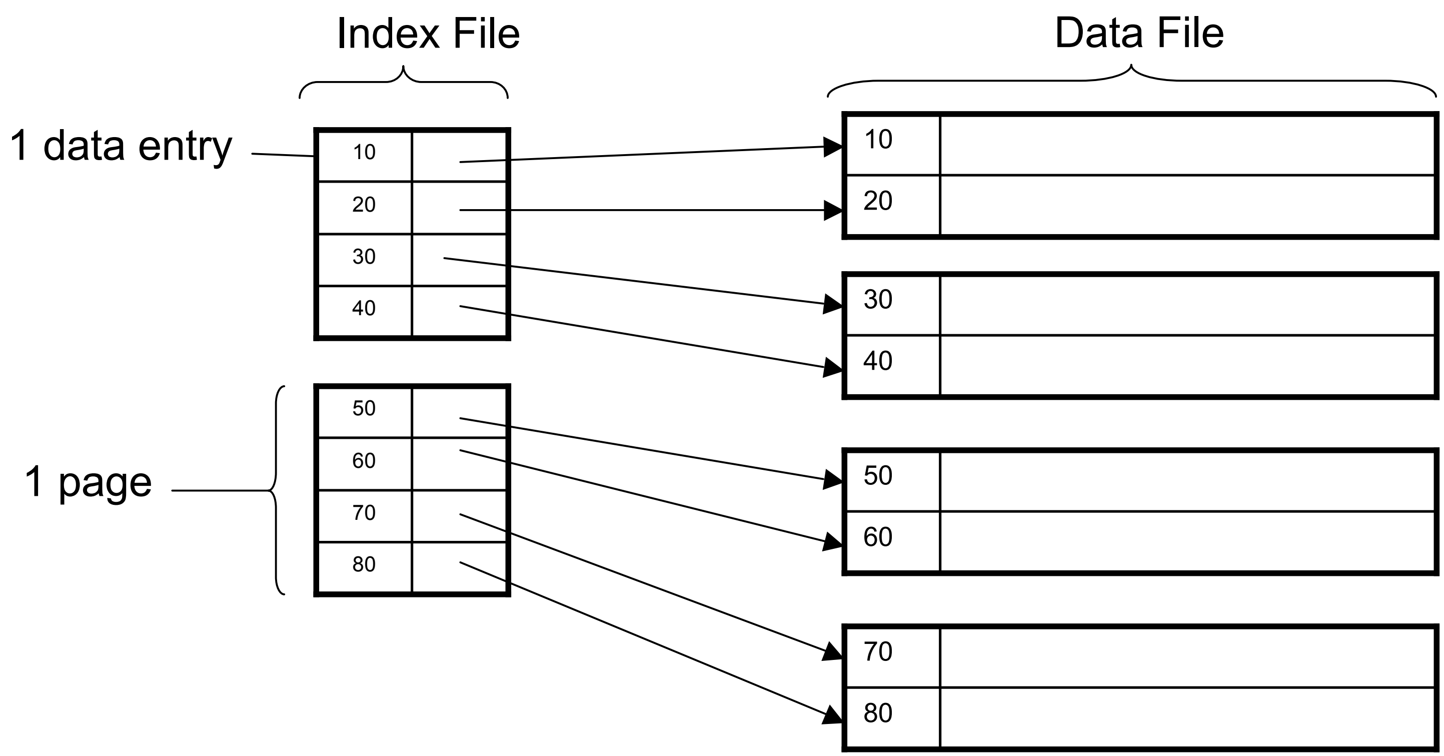
- **Search key** = can be any set of fields
  - not the same as the primary key, nor a key

- **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**
    - This type of index is also called the **primary index** of a file
  - (k, RID)
  - (k, list-of-RIDs)

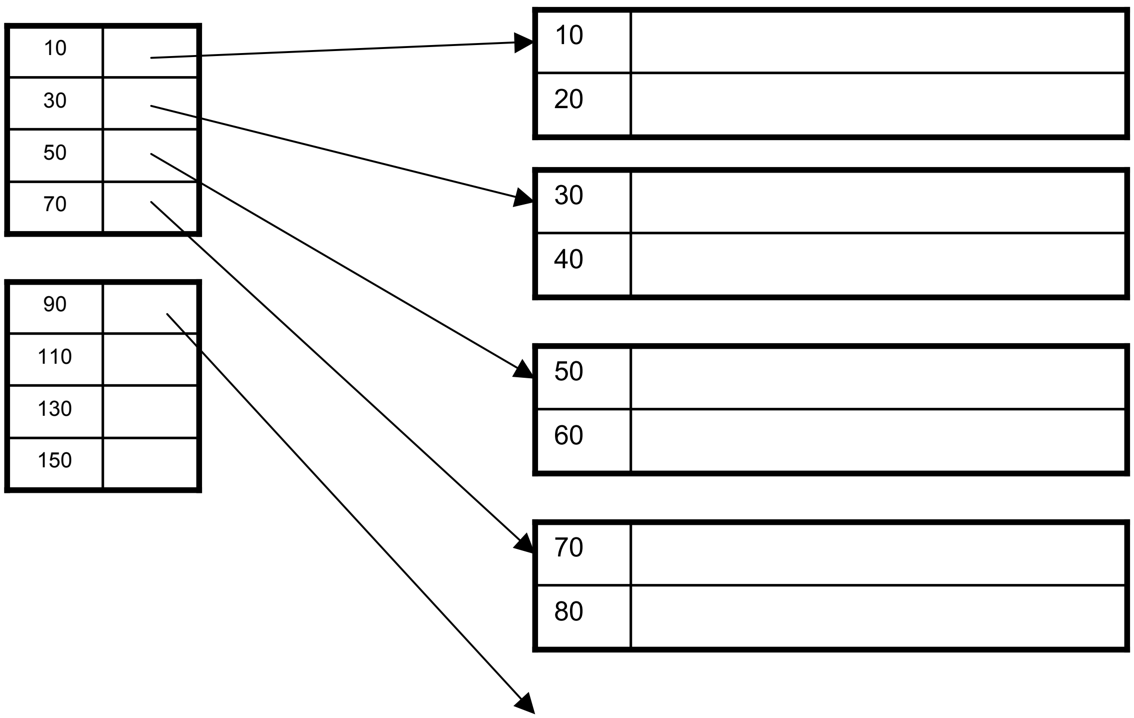
Primary Index

- Data file is sorted on the index attribute
- *Dense* index: sequence of (key,pointer) pairs



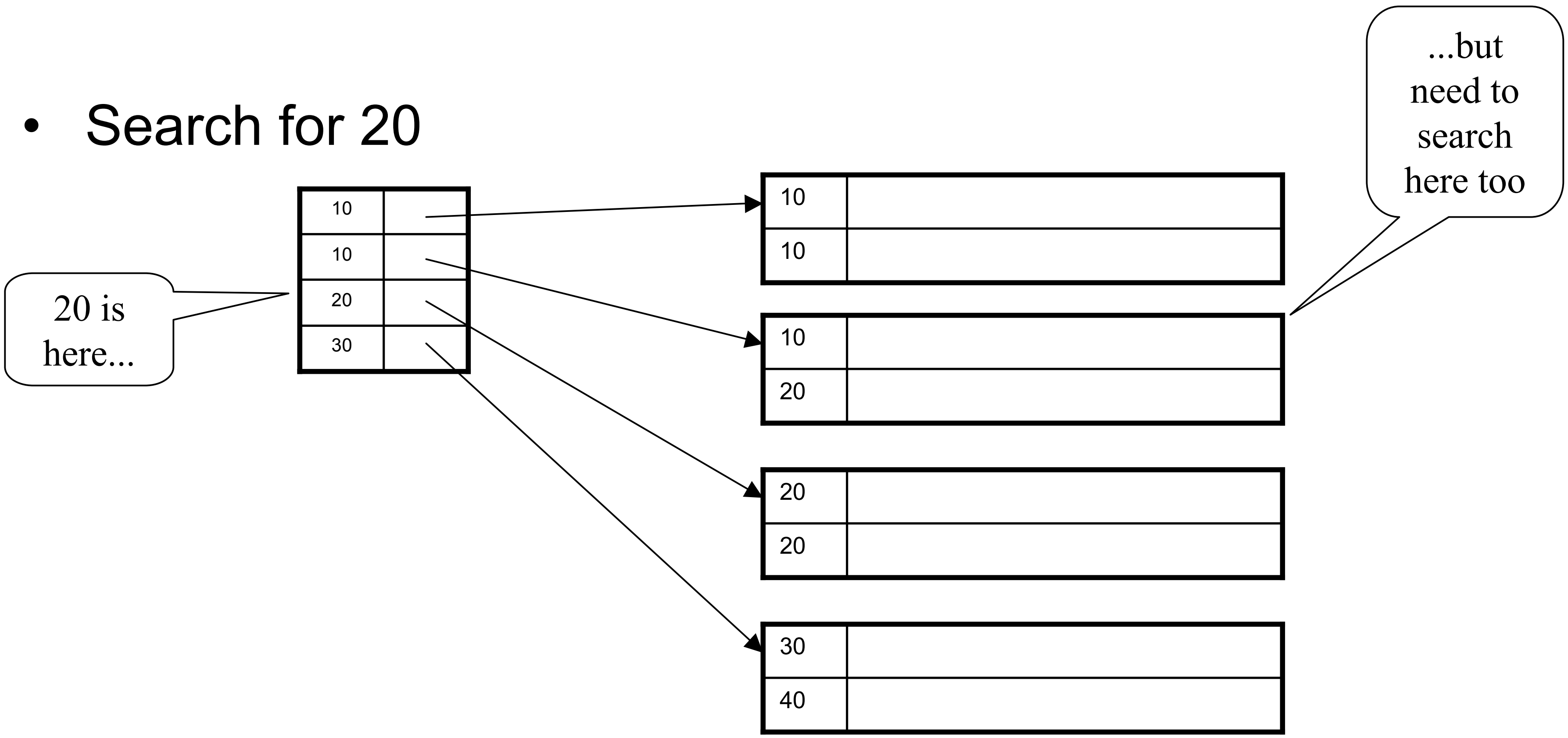
Primary Index

- *Sparse* index



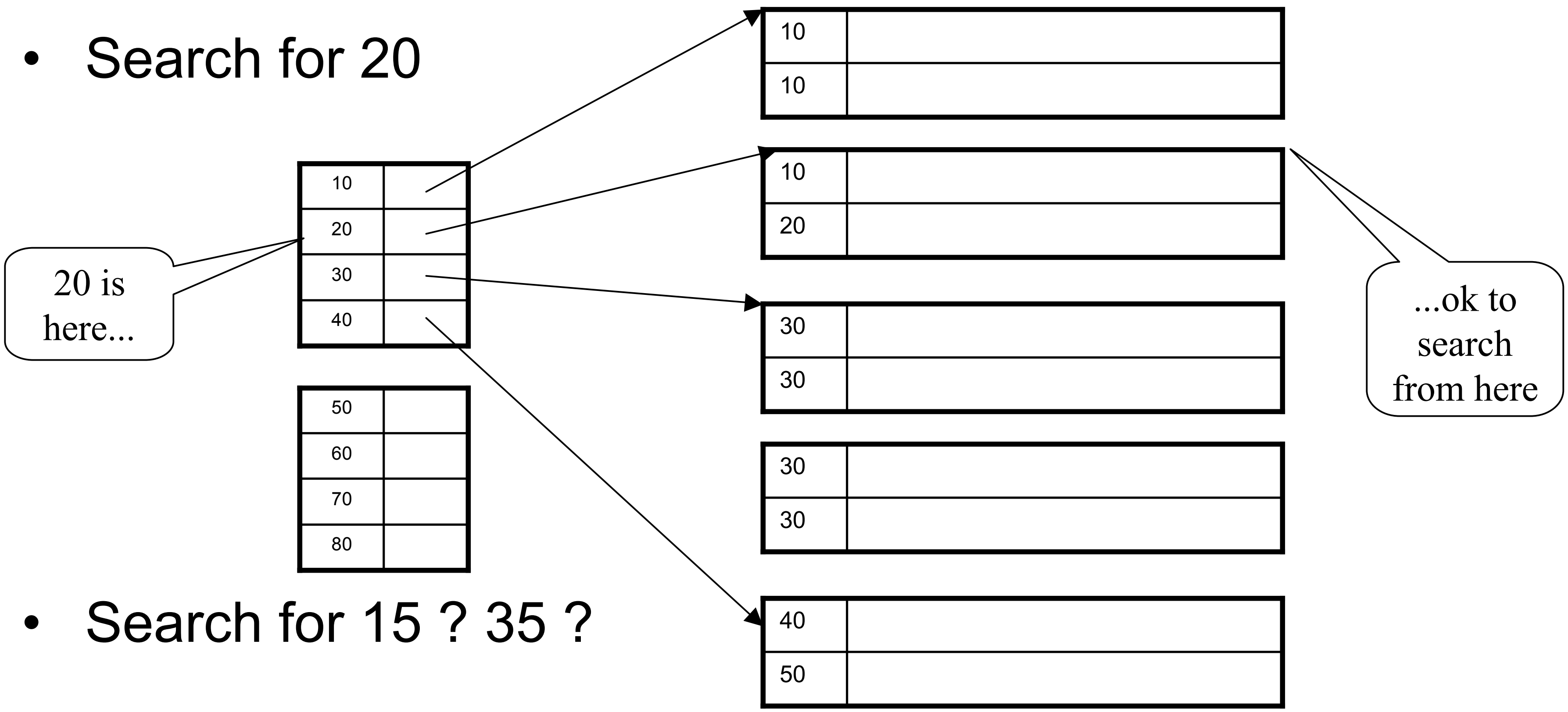
Primary Index with Duplicate Keys

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



Primary Index with Duplicate Keys

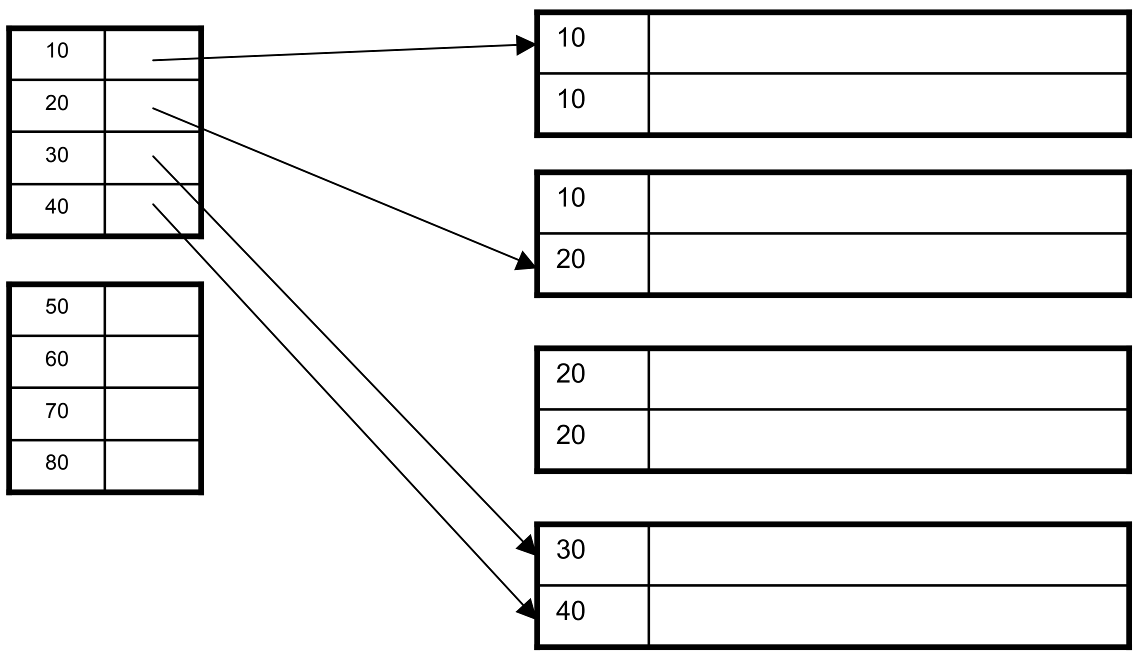
- Better: pointer to ***lowest new search key*** on each page:
- Search for 20



- Search for 15 ? 35 ?

Primary Index with Duplicate Keys

- Dense index:



Primary Index Example

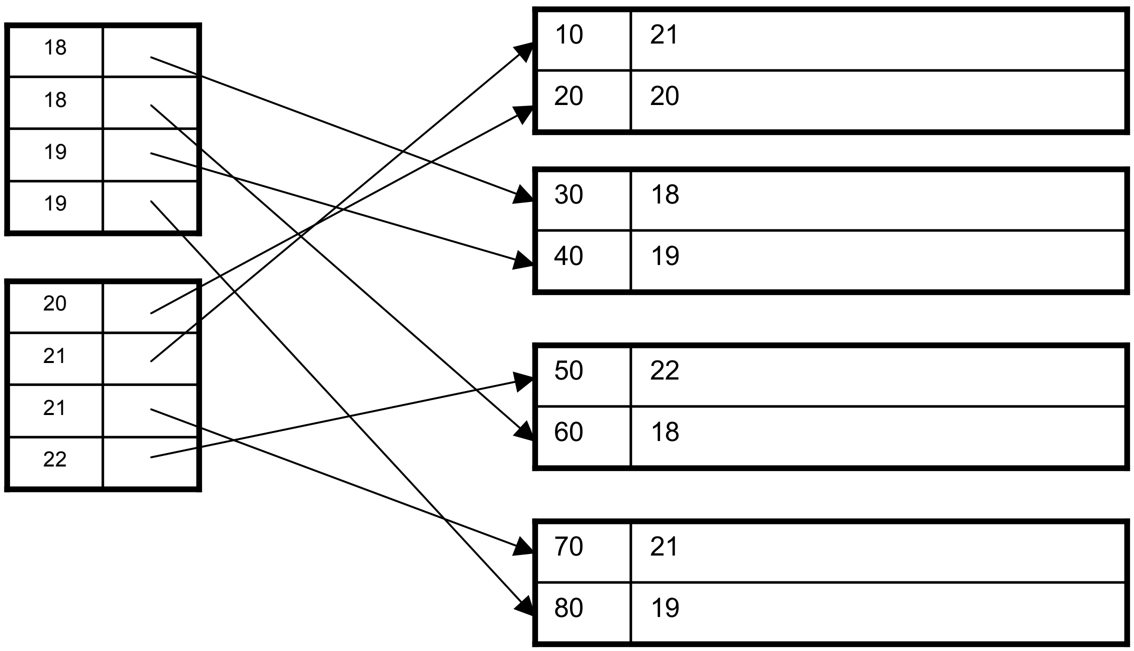
- Let's assume all pages of index fit in memory

- 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.

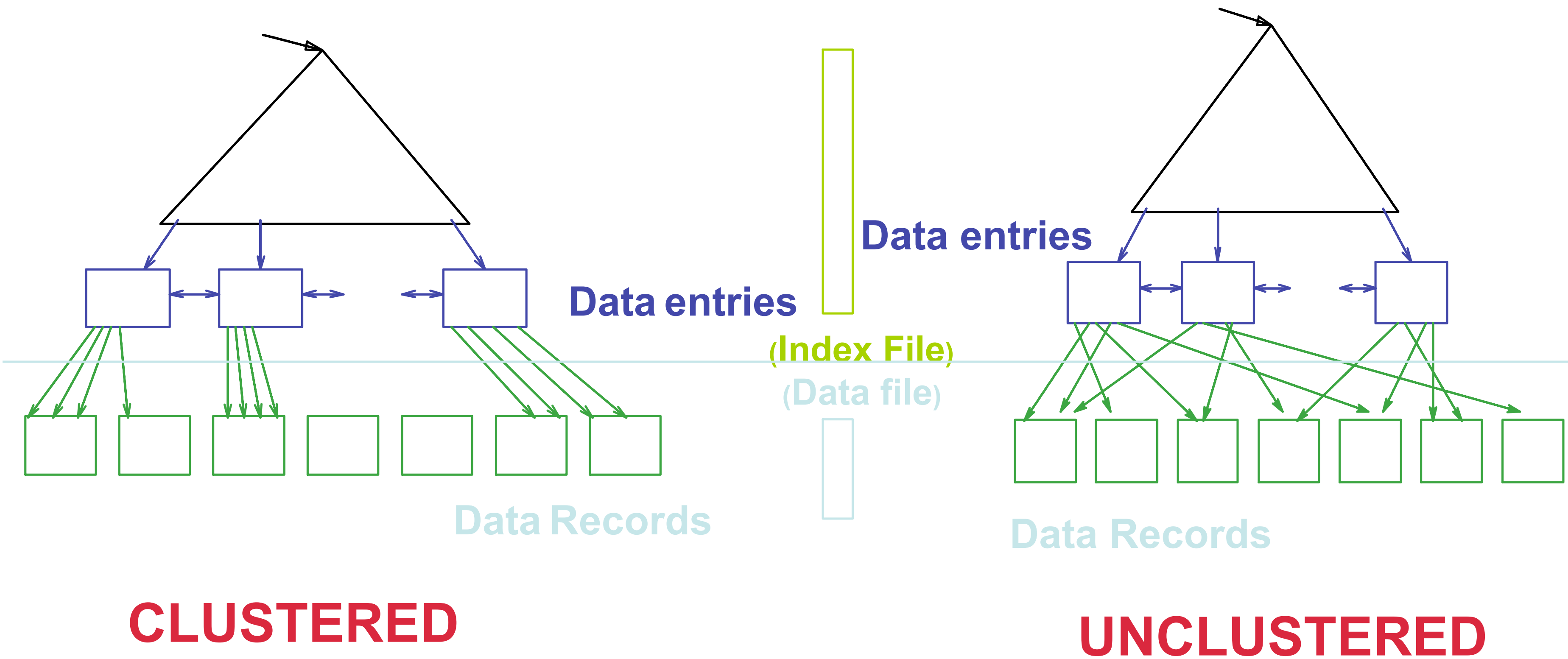
- How can we make *both* queries fast?

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 clustered data

Index Classification Summary

- Primary/secondary
  - Primary = determines the location of indexed records (i.e., data order)
  - 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 / …

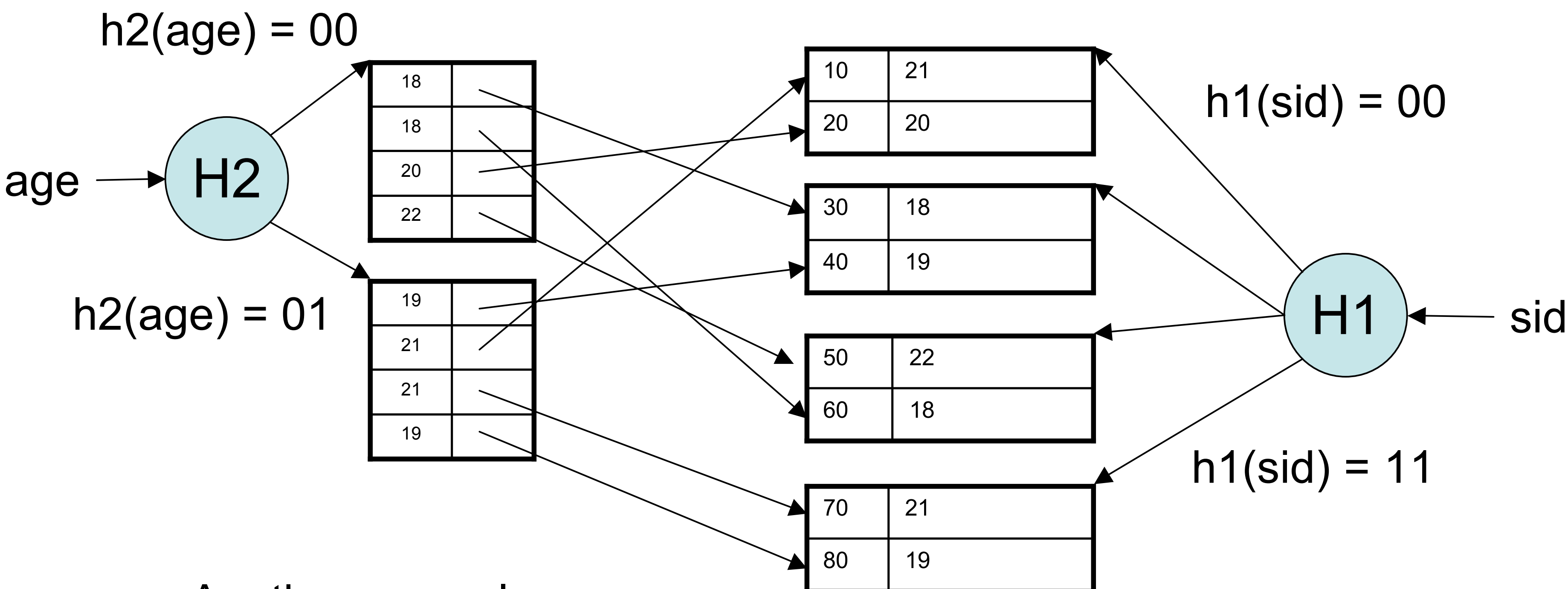
Large Indexes

- 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



Another example of secondary index

Another example of primary index

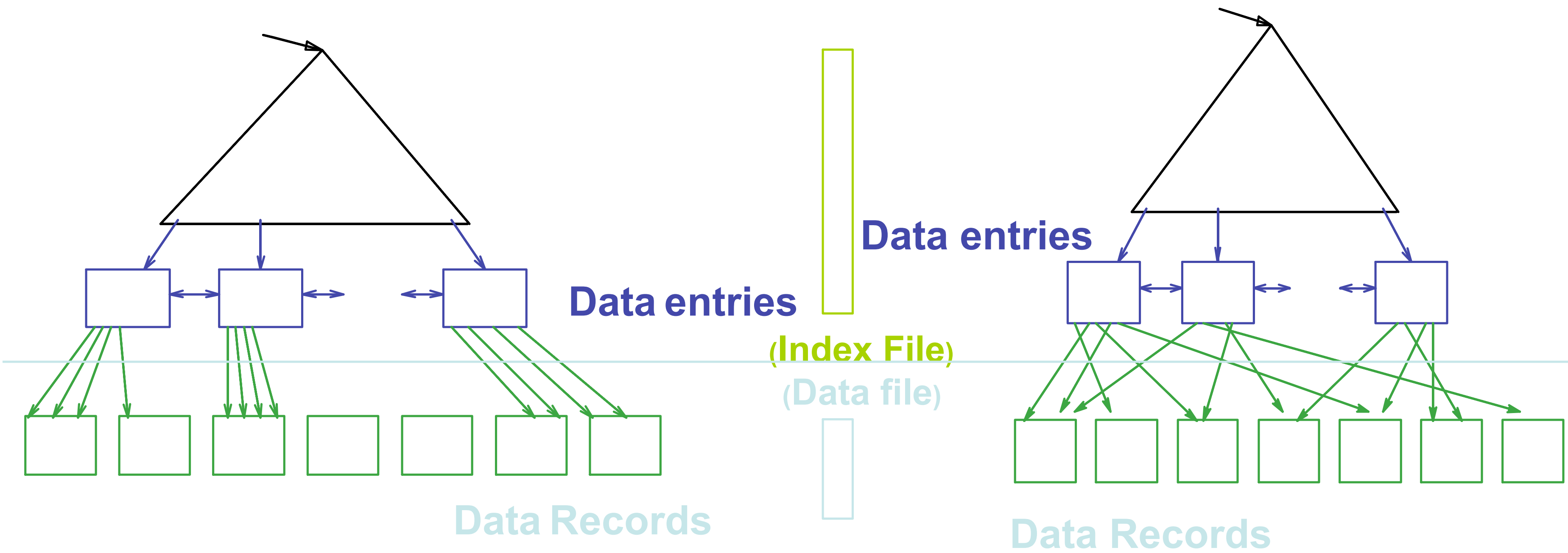
Tree-Based Index

- 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

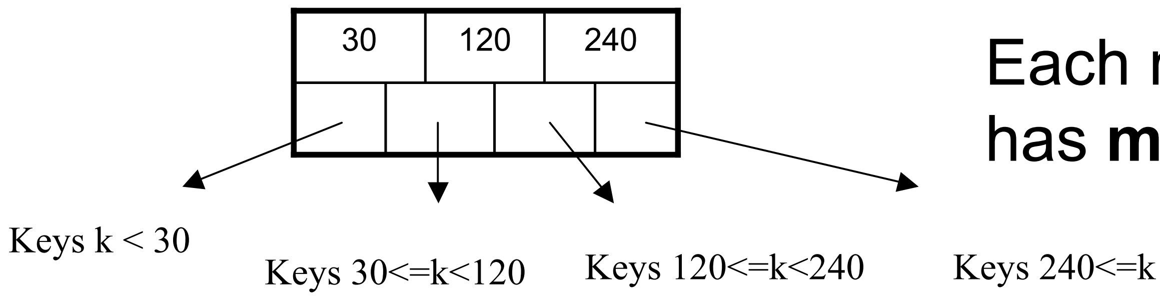


CLUSTERED **UNCLUSTERED**

Note: can also store data records directly as data entries (primary index)

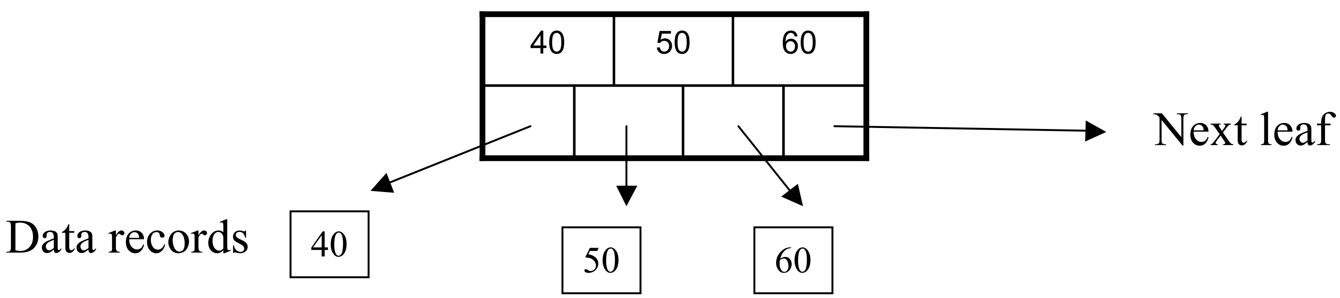
B+ Trees Basics

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



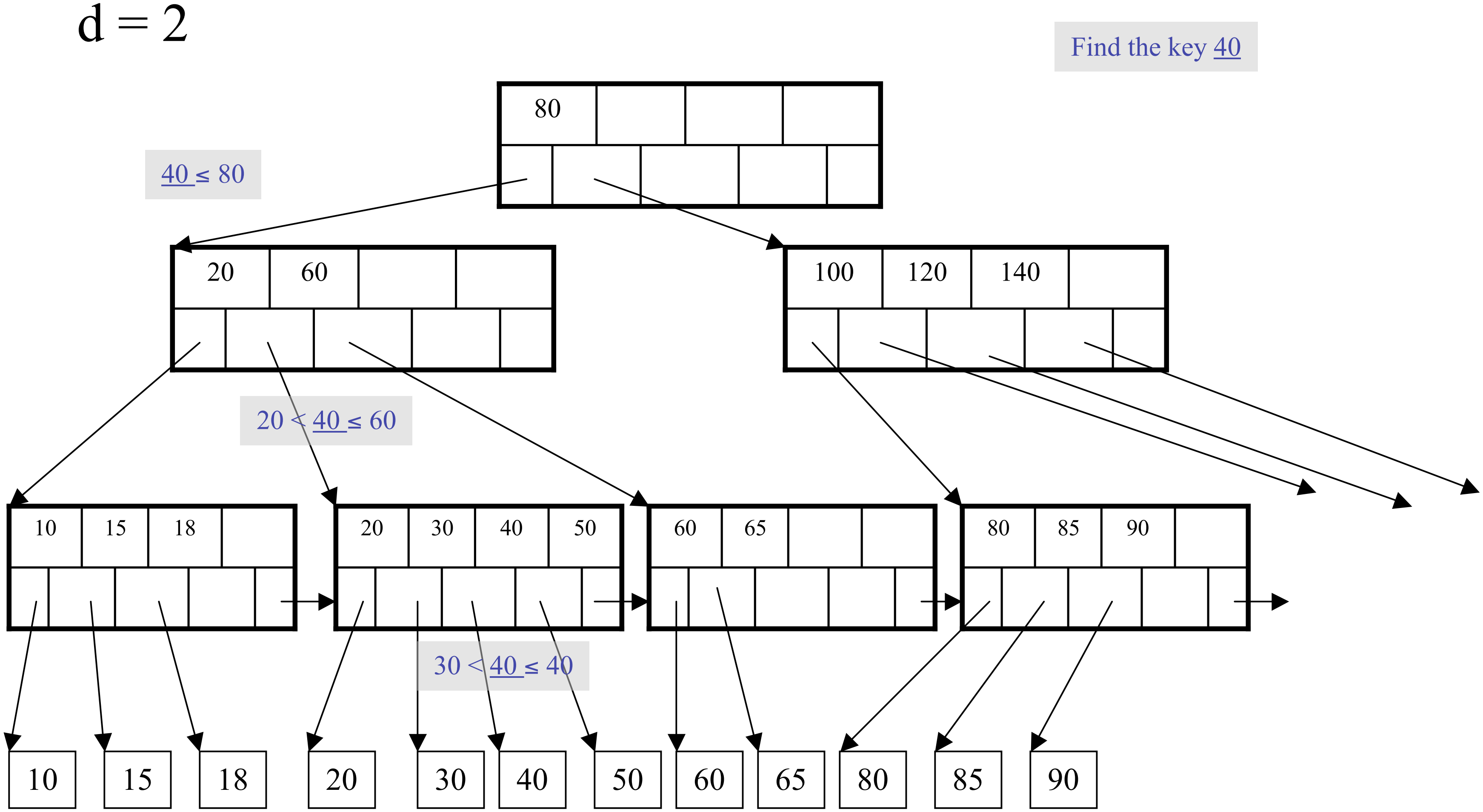
Each node also has **m+1 pointers**

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



B+ Tree Example

d = 2



Searching a B+ Tree

- Exact key values:
  - Start at the root
  - Proceed down, to the leaf
- Range queries:
  - Find lowest bound as above
  - Then sequential traversal

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

```
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

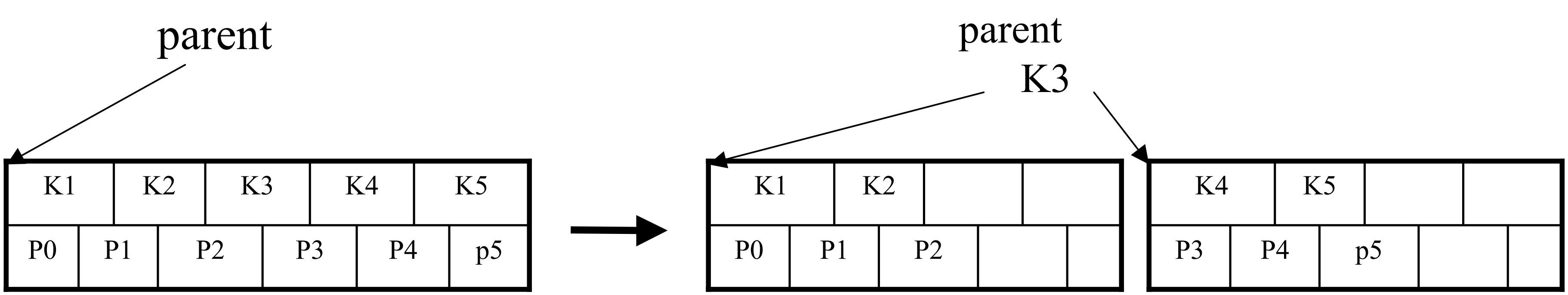
B+ Trees in Practice

- 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)

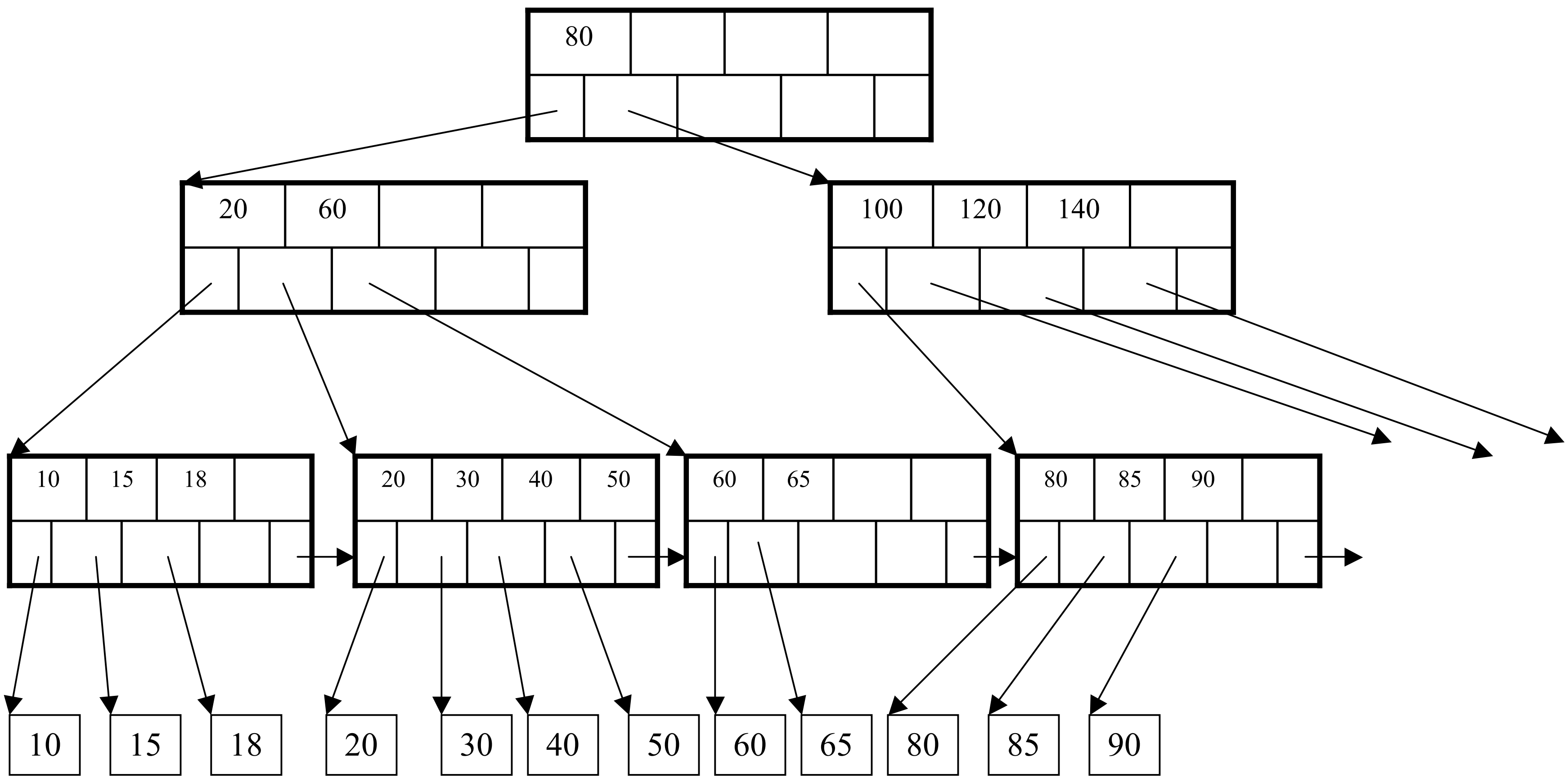
- Find leaf where K belongs, insert
- If no overflow (2d keys or less), halt
- If overflow (2d+1 keys), split node, insert in parent:



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

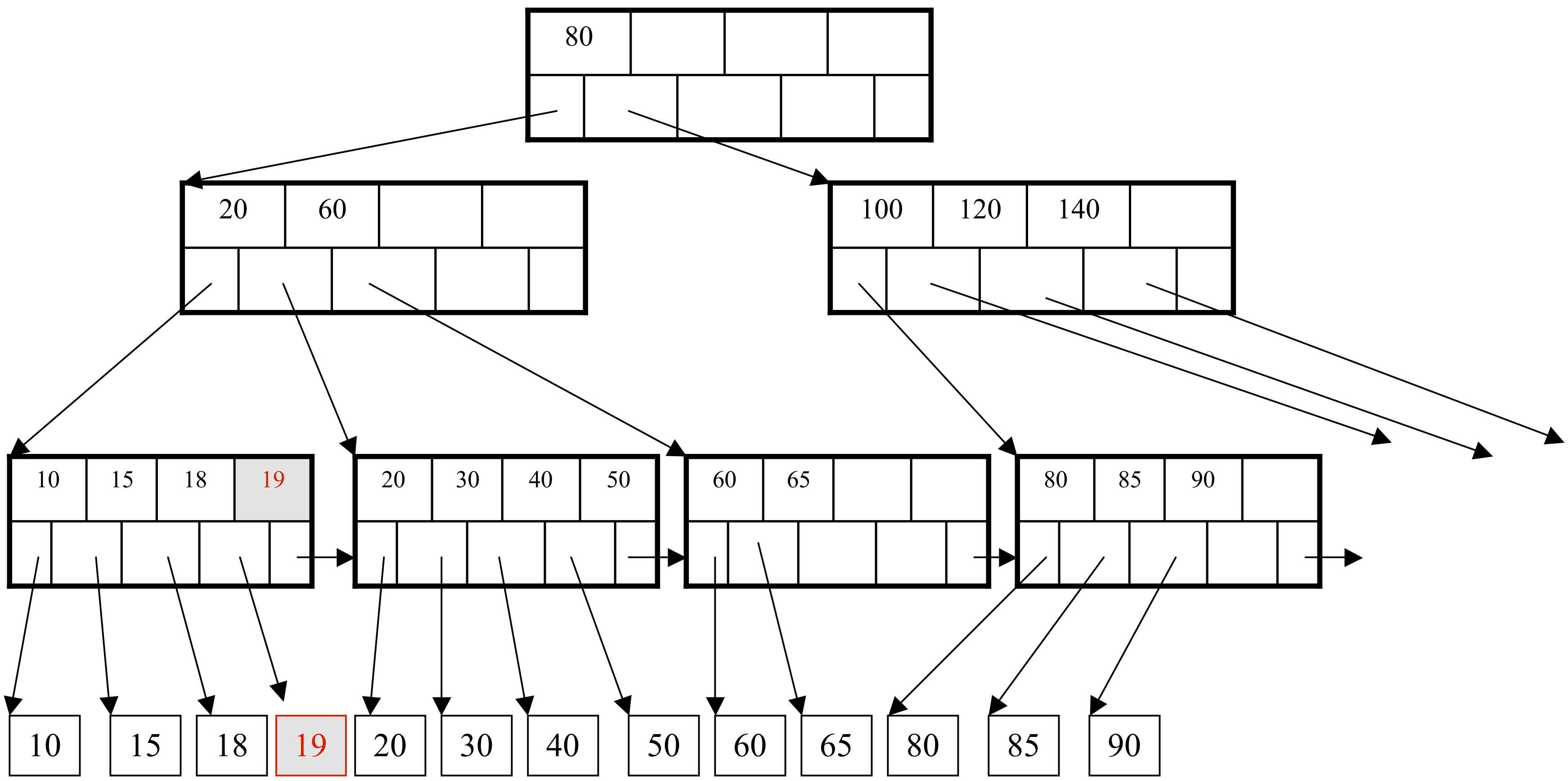
Insertion in a B+ Tree

Insert K=19



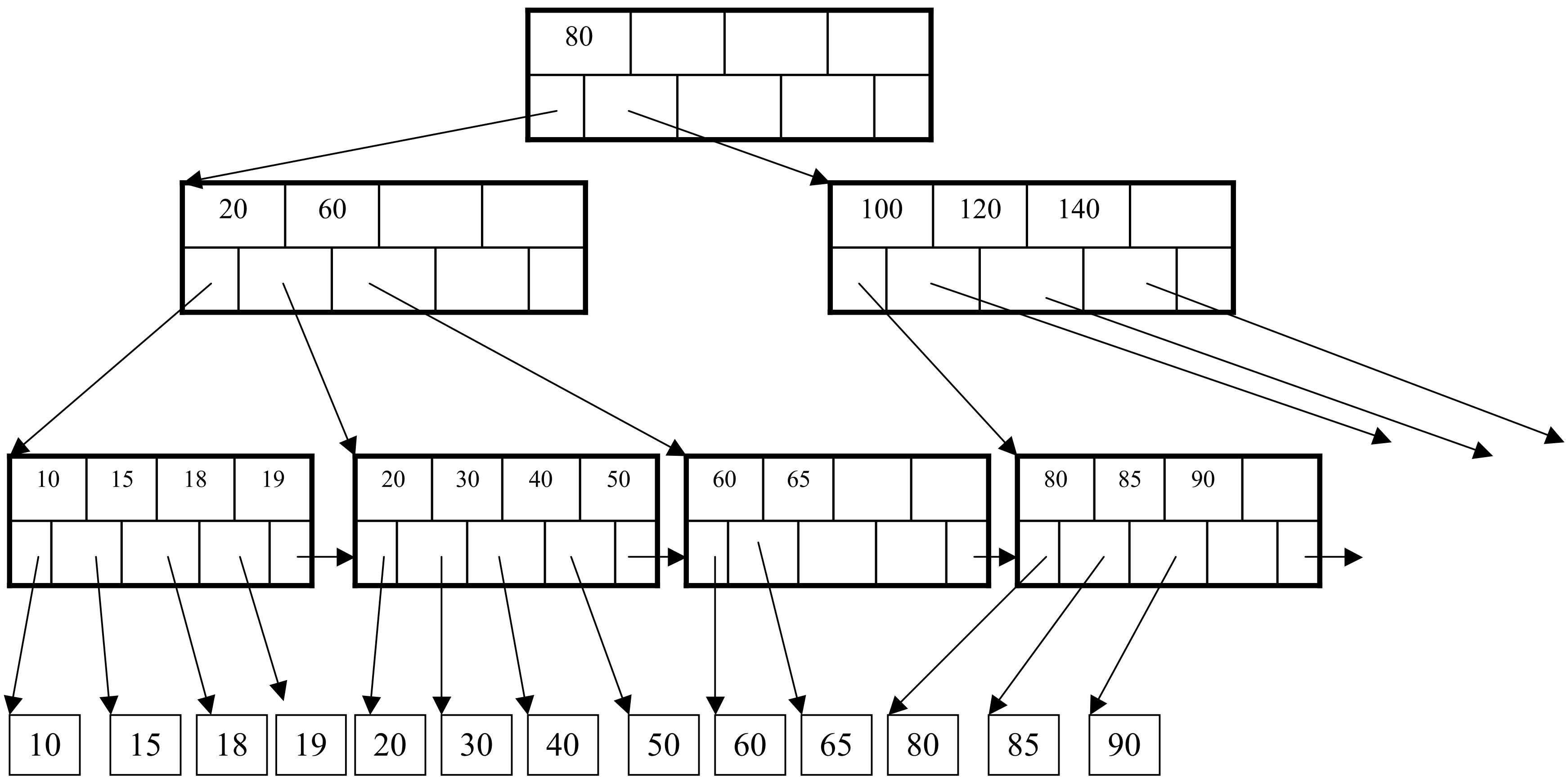
Insertion in a B+ Tree

After insertion



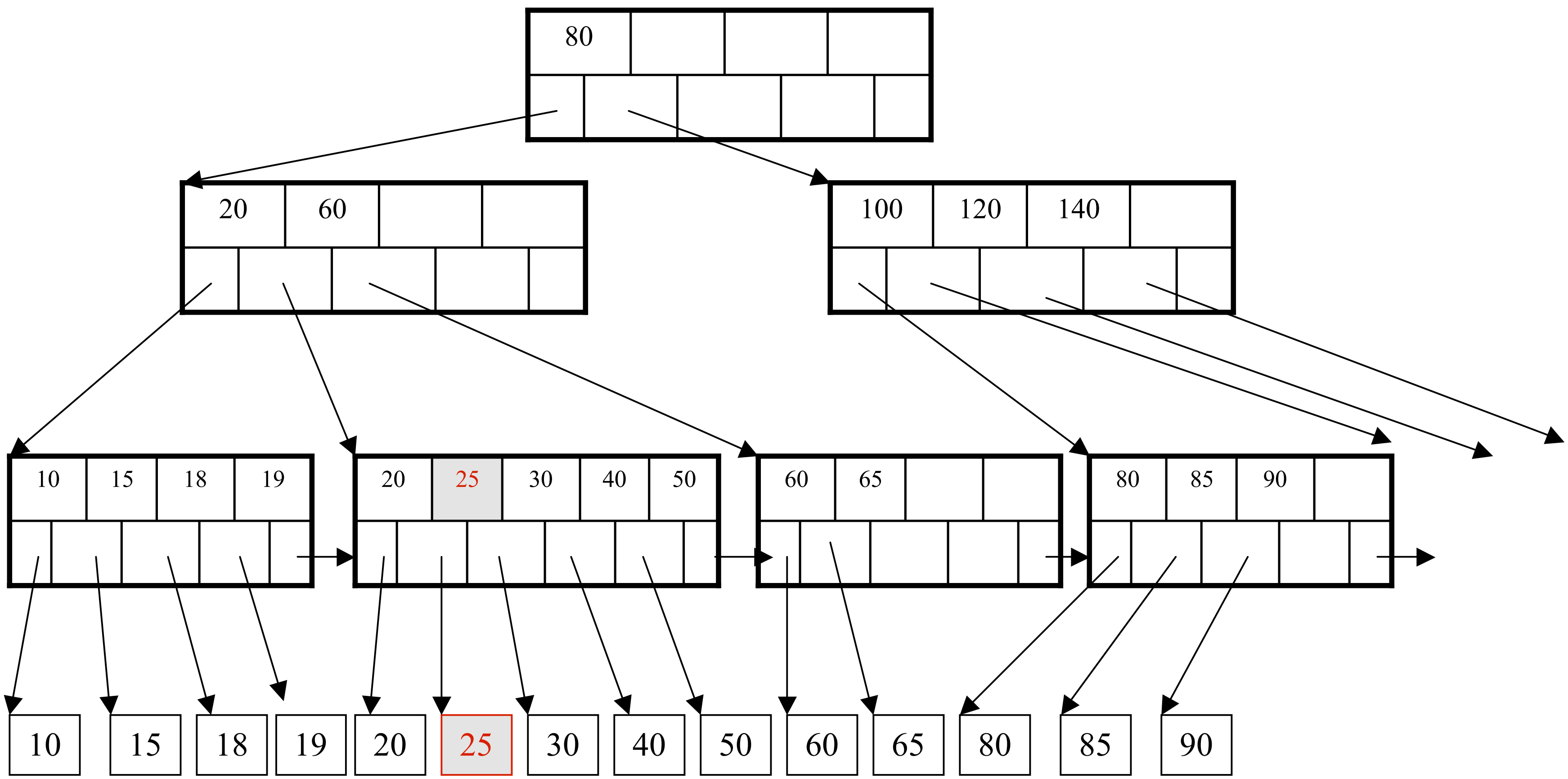
Insertion in a B+ Tree

Now insert 25



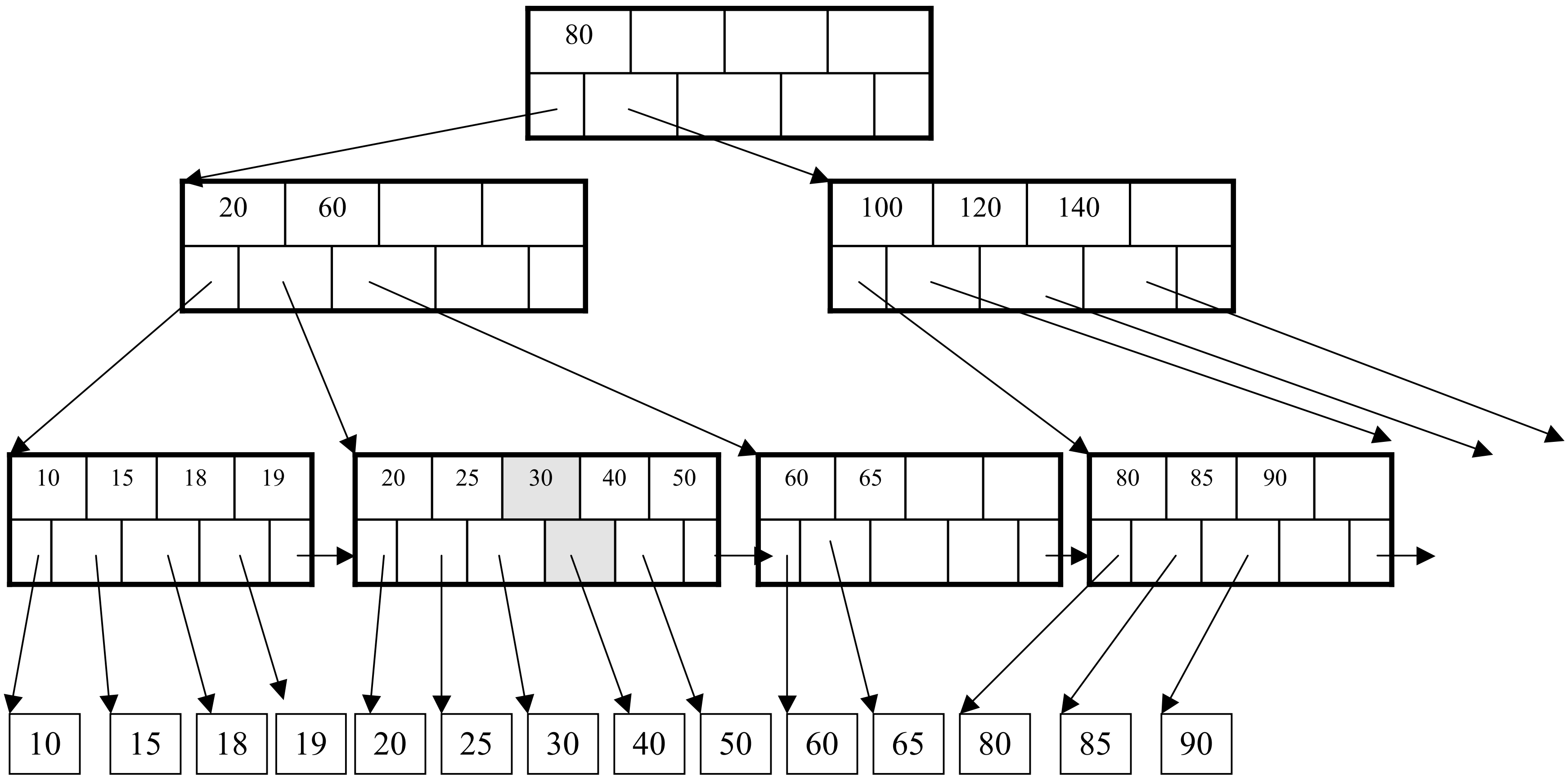
Insertion in a B+ Tree

After insertion



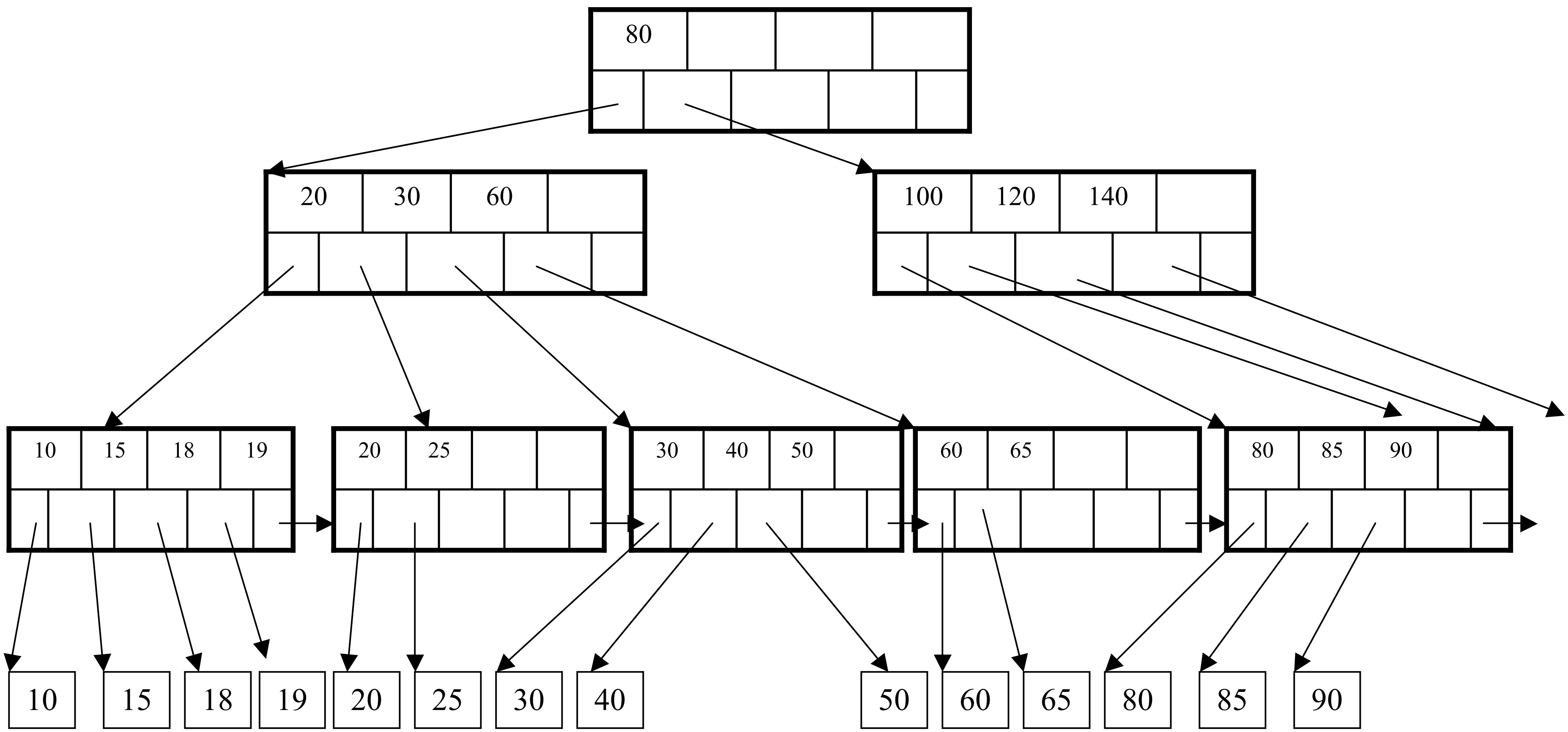
Insertion in a B+ Tree

But now have to split !



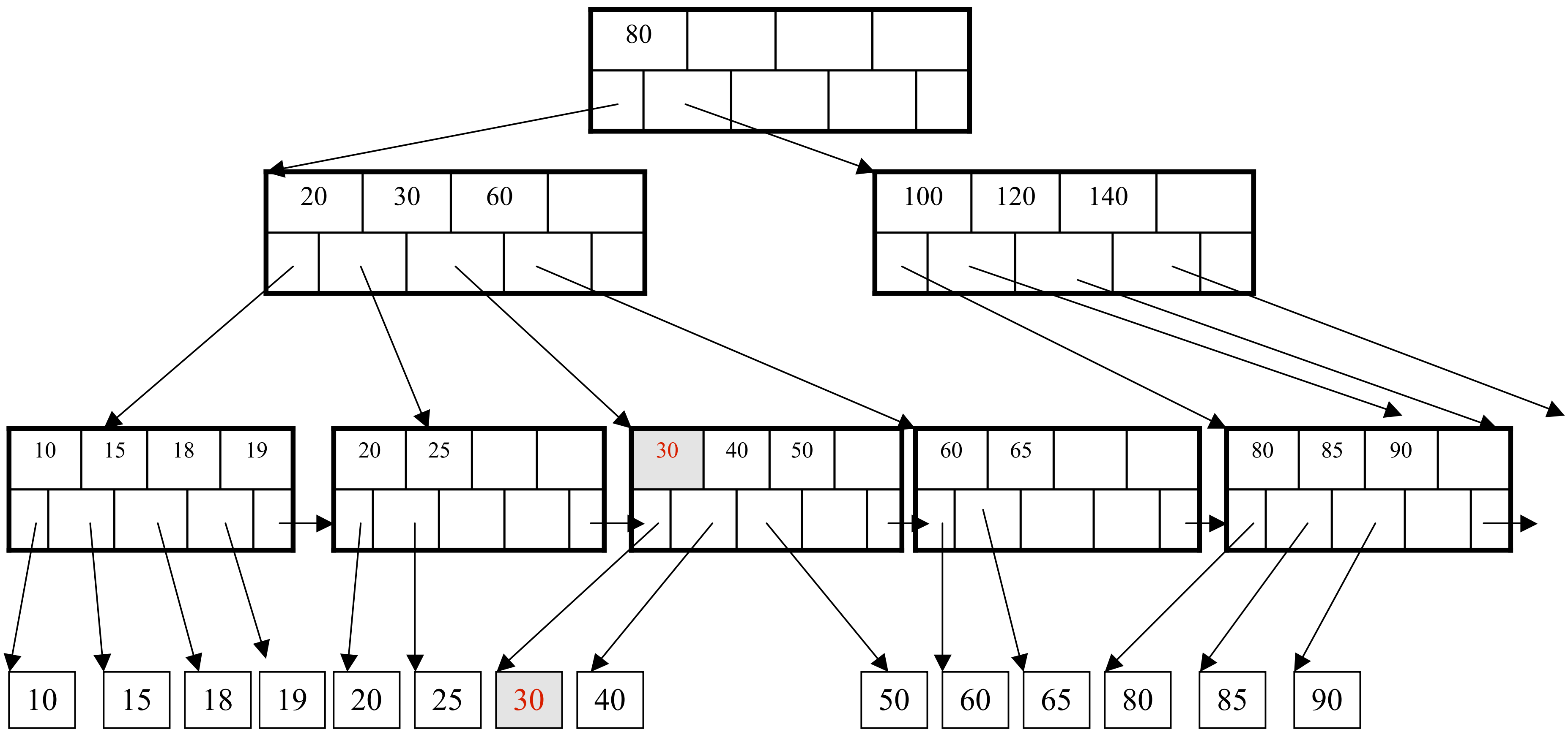
Insertion in a B+ Tree

After the split



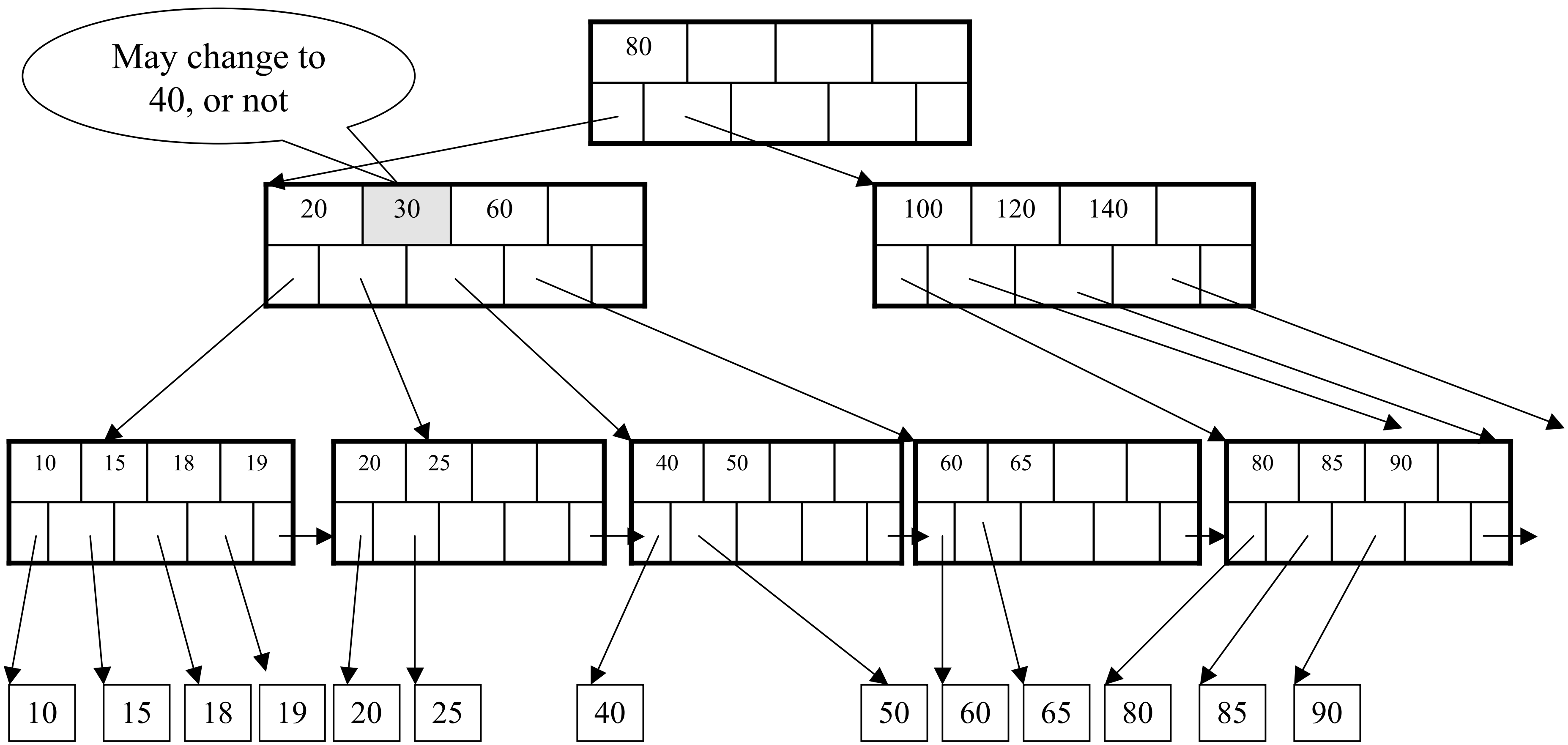
Deletion from a B+ Tree

Delete 30



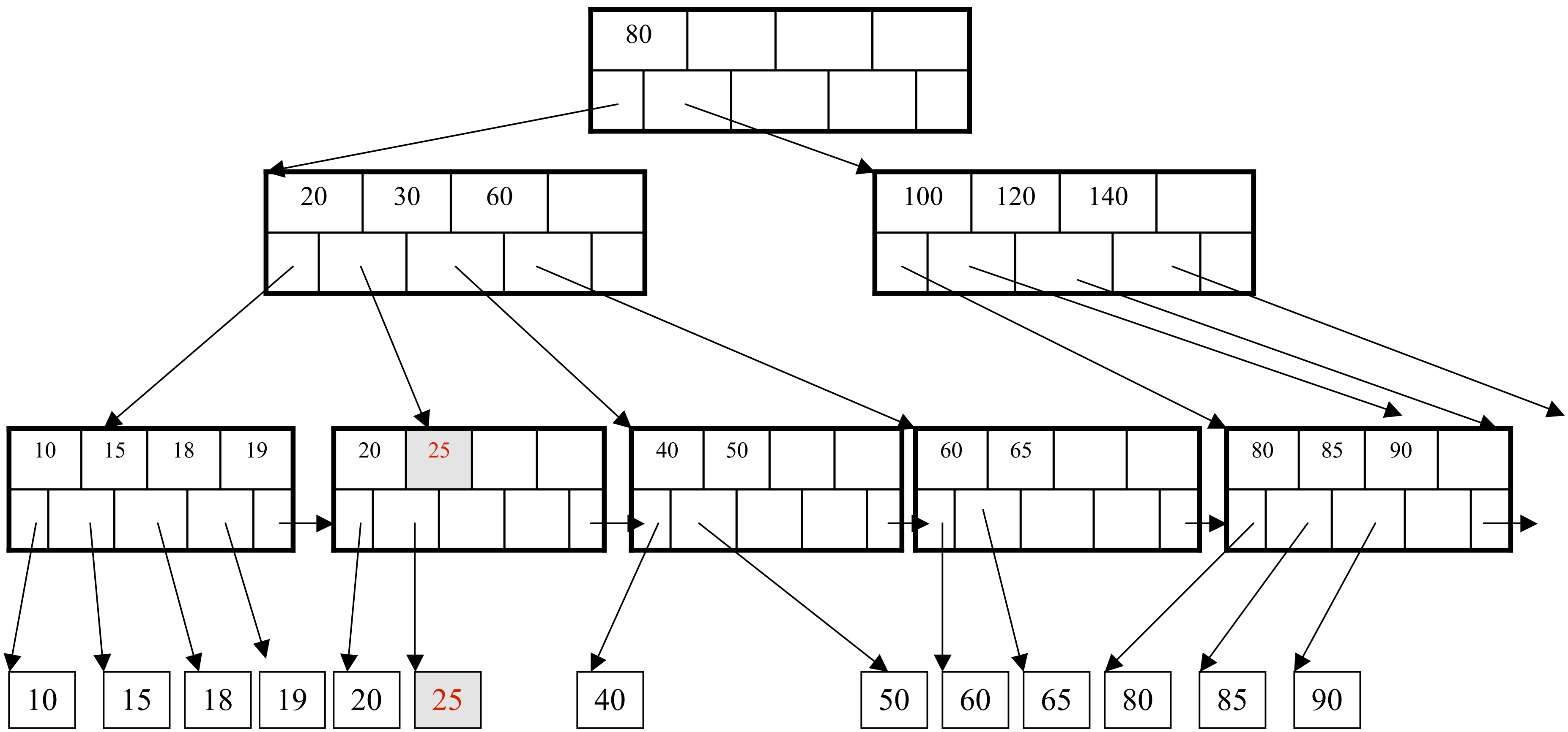
Deletion from a B+ Tree

After deleting 30



Deletion from a B+ Tree

Now delete 25

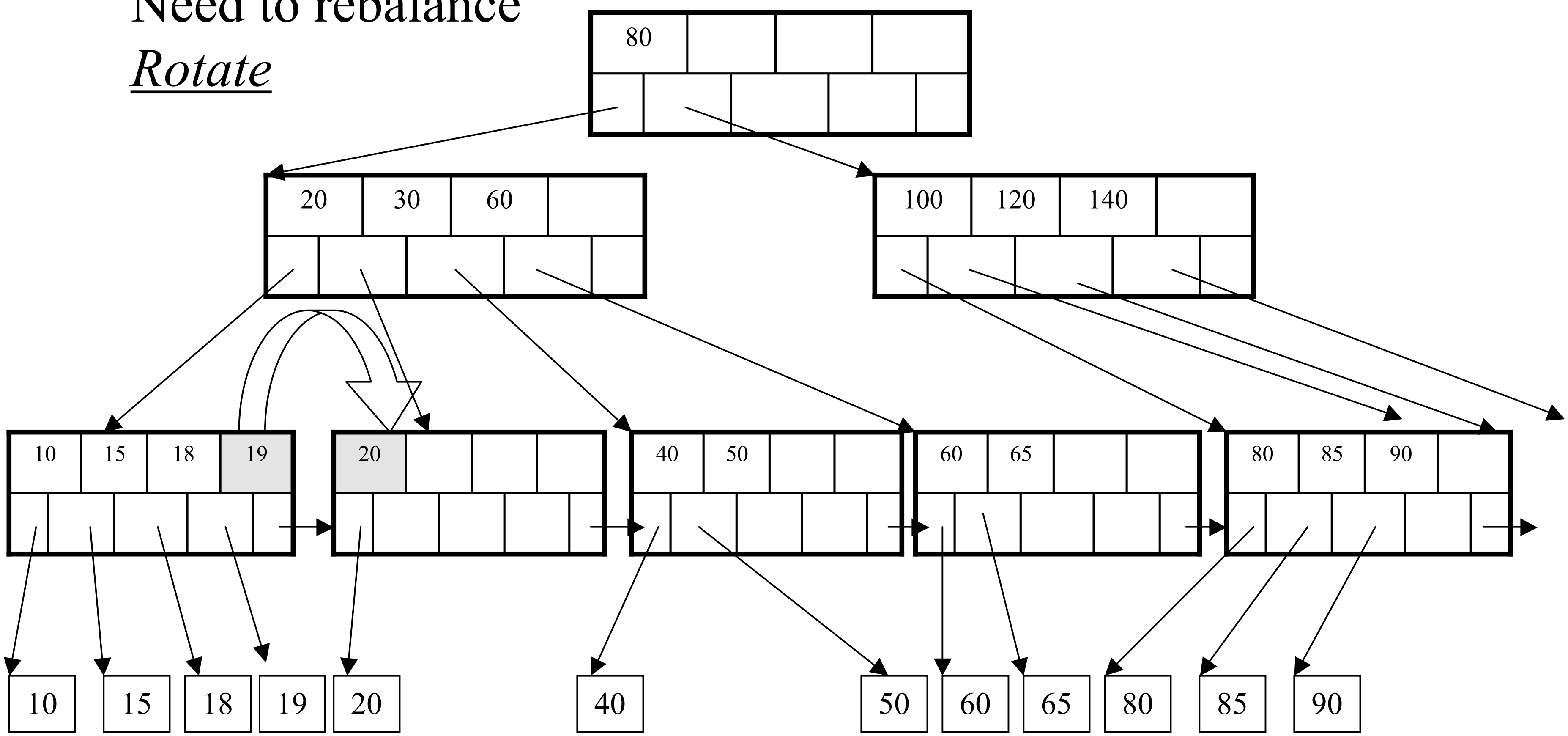


Deletion from a B+ Tree

After deleting 25

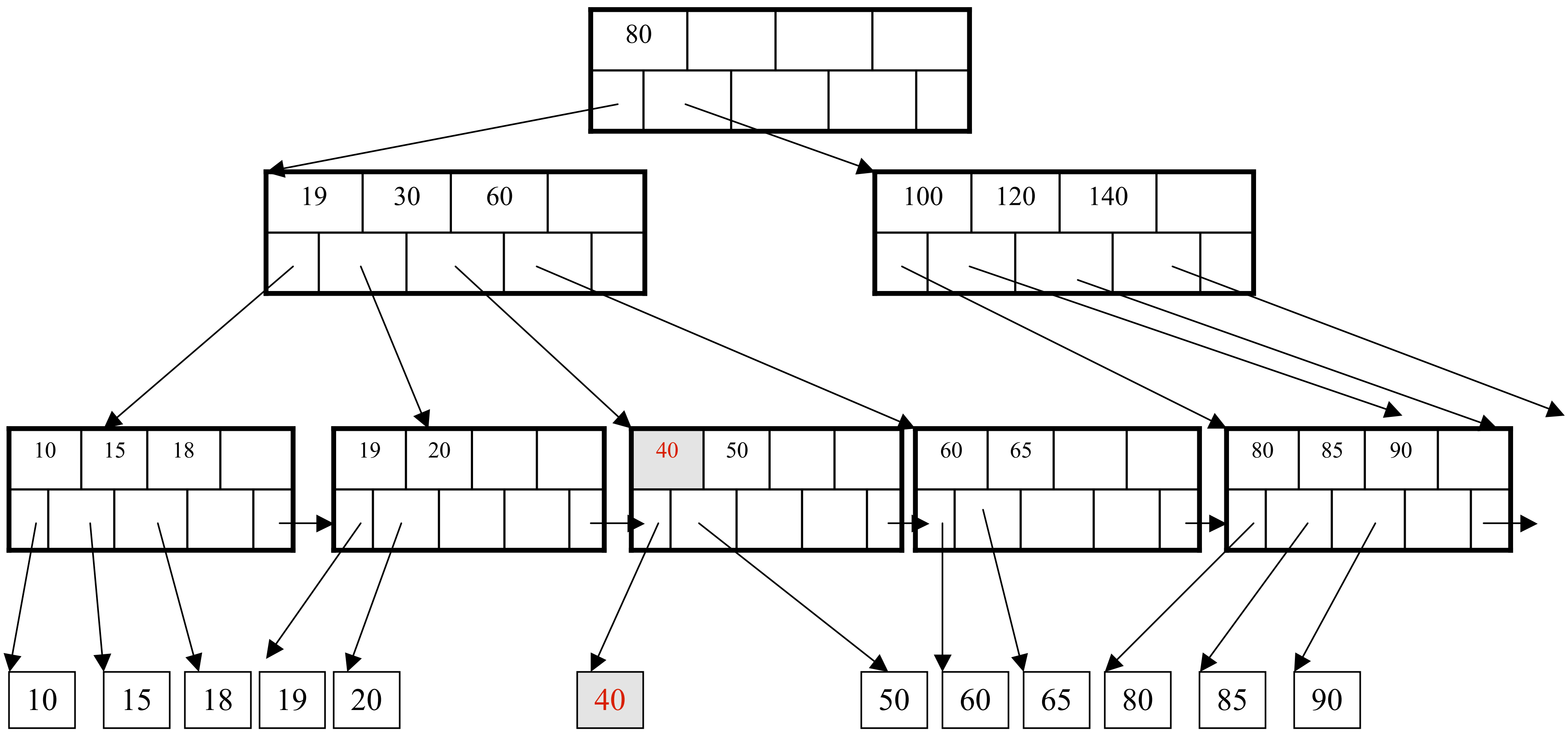
Need to rebalance

Rotate



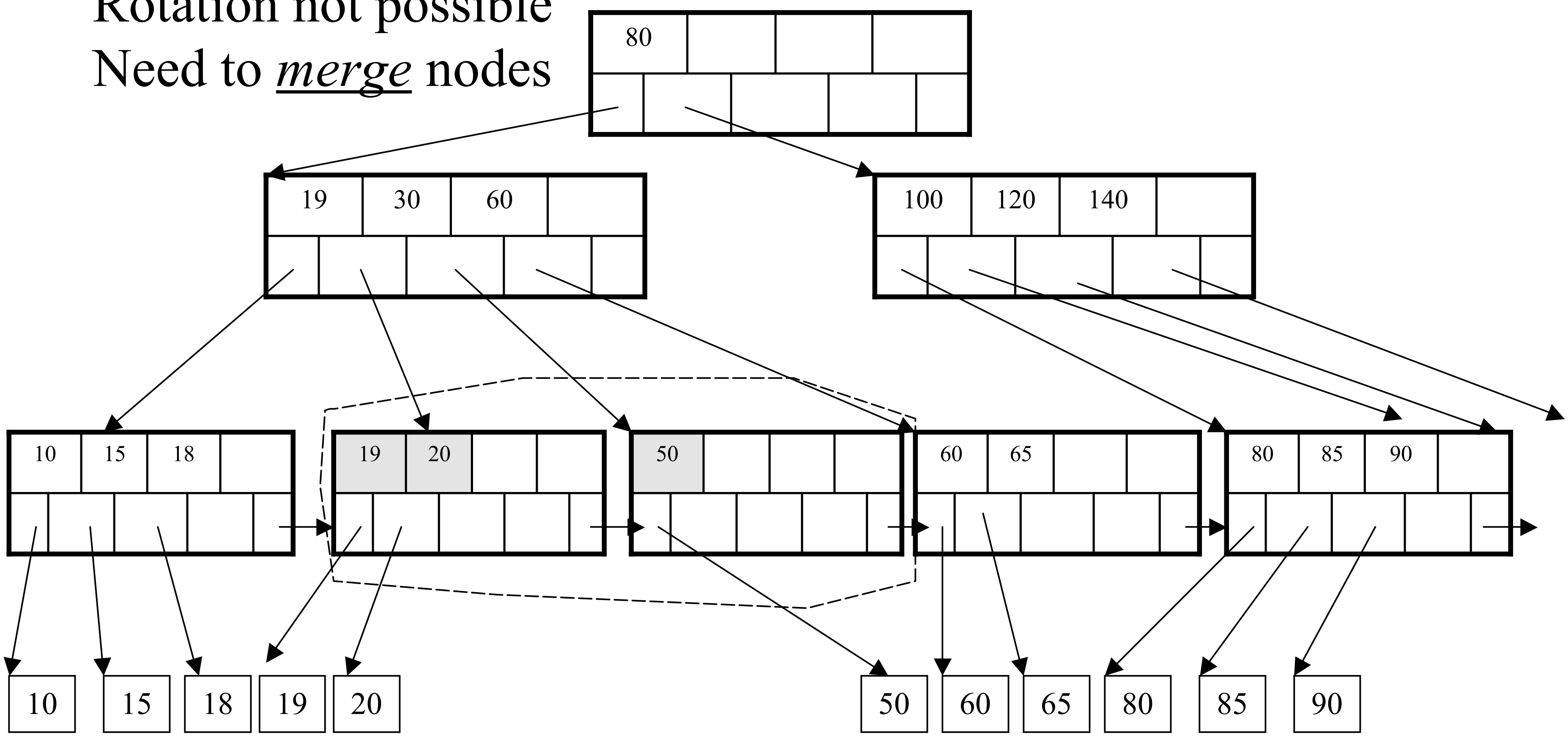
Deletion from a B+ Tree

Now delete 40



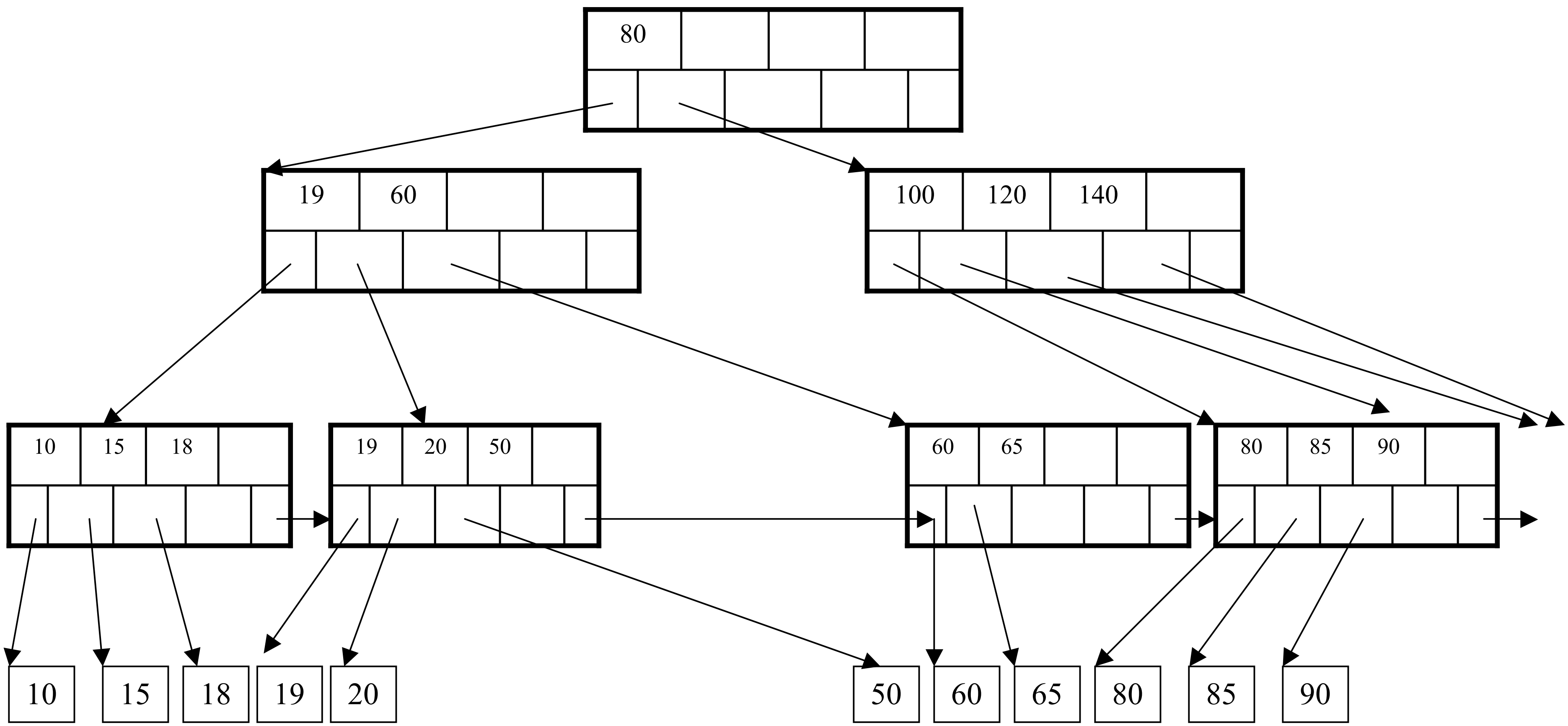
Deletion from a B+ Tree

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

Generalized Search Tree (GiST)

- Goal: facilitate database extensibility
  - When adding a new data type
  - Want to add indexes for the data type

- Overview
  - GiST is an index structure
  - Basically, this is a template for indexes
  - Supports extensible set of queries and data types

- We will finish talking about GiST next lecture