CSE 544
Principles of Database Management Systems

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Fall 2015

Lecture 5 - DBMS Architecture and Indexing

Announcements

- HW1 is due next Thursday
  - How is it going?
- Projects:
  - Proposals are due next Wednesday (not graded)
  - Submit on dropbox

Where We Are

- **What we have already seen**
  - **Overview of the relational model**
    - Motivation and where model came from
    - Physical and logical independence
  - **How to design a database**
    - From ER diagrams to conceptual design
    - Schema normalization
  - **How different data models work**

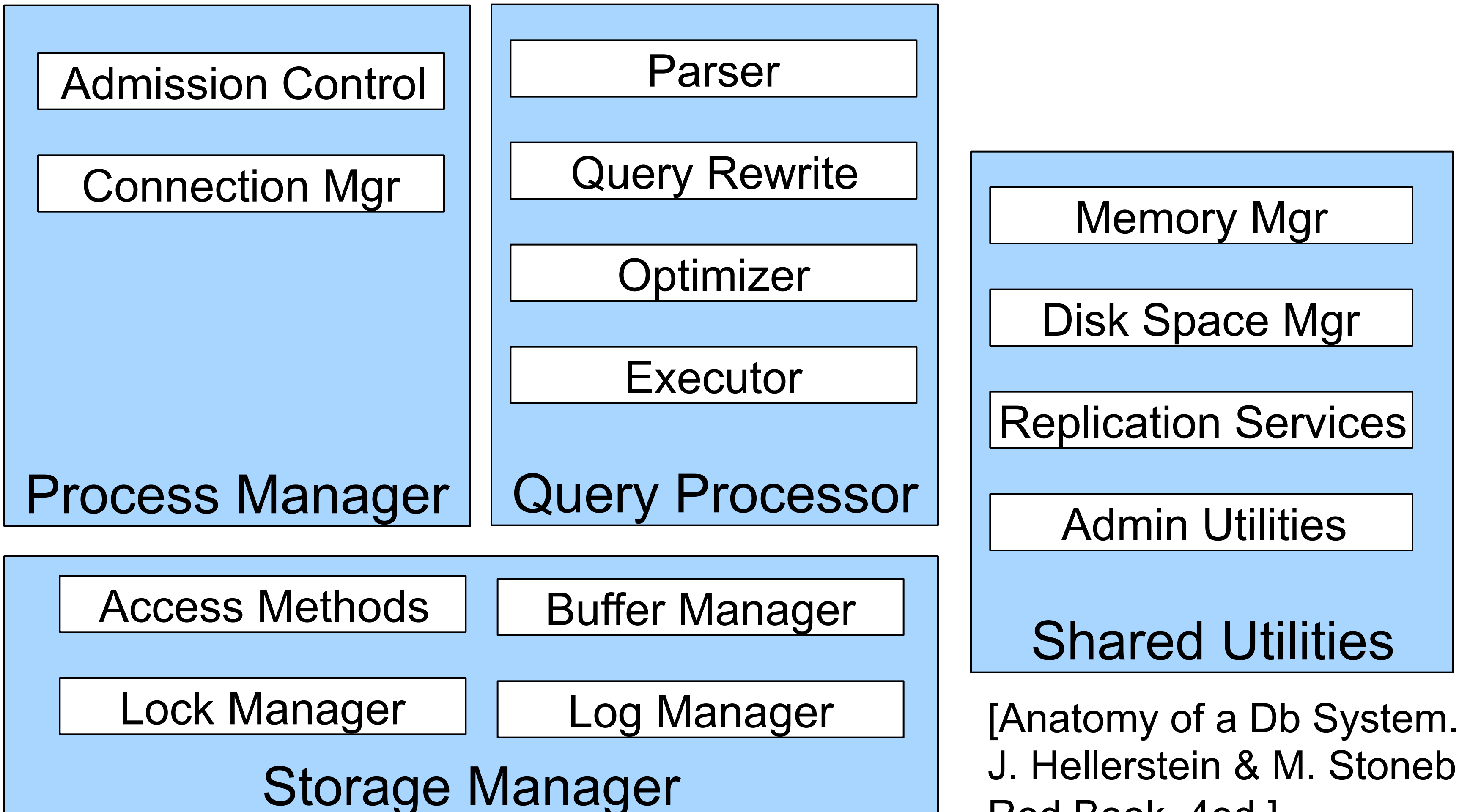
- **Where we go from here**
  - **How can we efficiently implement this model?**
  - **How can we run RA plans efficiently?**

References

- Anatomy of a database system. J. Hellerstein and M. Stonebraker. In Red Book (4th ed).

- Chapters 8 through 11 (in the R&G book, third ed.)
  - Disk and files: Sections 9.3 through 9.7
  - Index structures: Section 8.3
  - Hash-based indexes: Section 8.3.1 and Chapter 11
  - B+ trees: Section 8.3.2 and Chapter 10

DBMS Architecture



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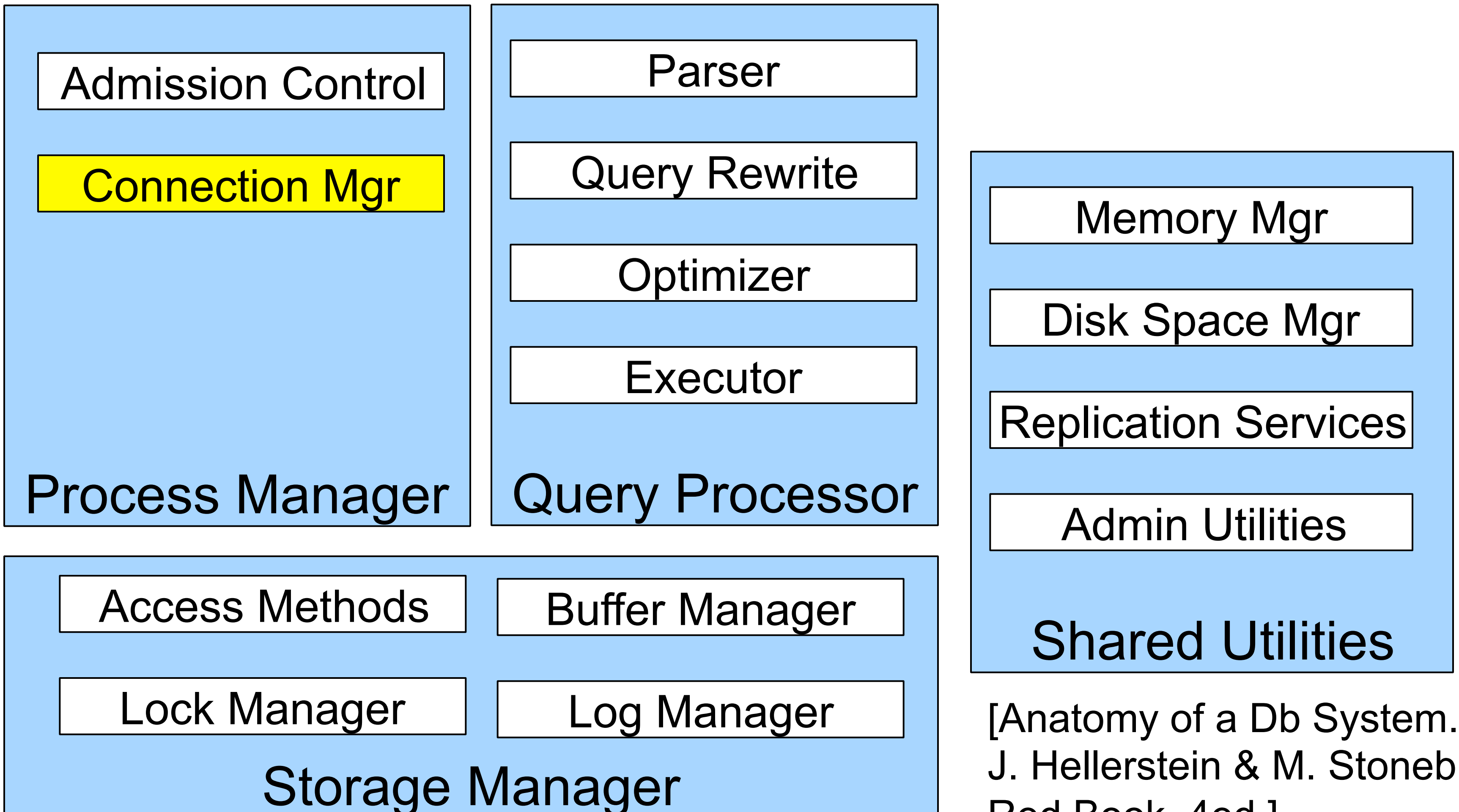
DBMS Architecture



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Process Model

Why not simply queue all user requests?
(and serve them one at the time)

Alternatives

1. **Process per connection**
2. **Server process** (thread per connection)
   - OS threads or DBMS threads
3. **Server process with I/O process**

Advantages and problems of each model?

Process Per Connection

- **Overview**
  - DB server forks one process for each client connection
- **Advantages**
  - Easy to implement (OS time-sharing, OS isolation, debuggers, etc.)
  - Provides more physical memory than a single process can use
- **Drawbacks**
  - Need OS support
    - Since all processes access the same data on disk, need concurrency control
  - Not scalable: memory overhead and expensive context switches
    - Goal is efficient support for high-concurrency transaction processing

Server Process

- **Overview**
  – DB assigns one thread per connection (from a thread pool)

- **Advantages**
  – Shared structures can simply reside on the heap
  – Threads are lighter weight than processes (memory, context switching)

- **Drawbacks**
  – Concurrent programming is hard to get right (race conditions, deadlocks)
  – Portability issues can arise when using OS threads
  – **Big problem**: entire process blocks on synchronous I/O calls
    - Solution 1: OS provides asynchronous I/O (true in modern OS)
    - Solution 2: Use separate process(es) for I/O tasks

DBMS Threads vs OS Threads

- **Why do some DBMSs implement their own threads?**
  - Legacy: originally, there were no OS threads
  - Portability: OS thread packages are not completely portable
  - Performance: fast task switching

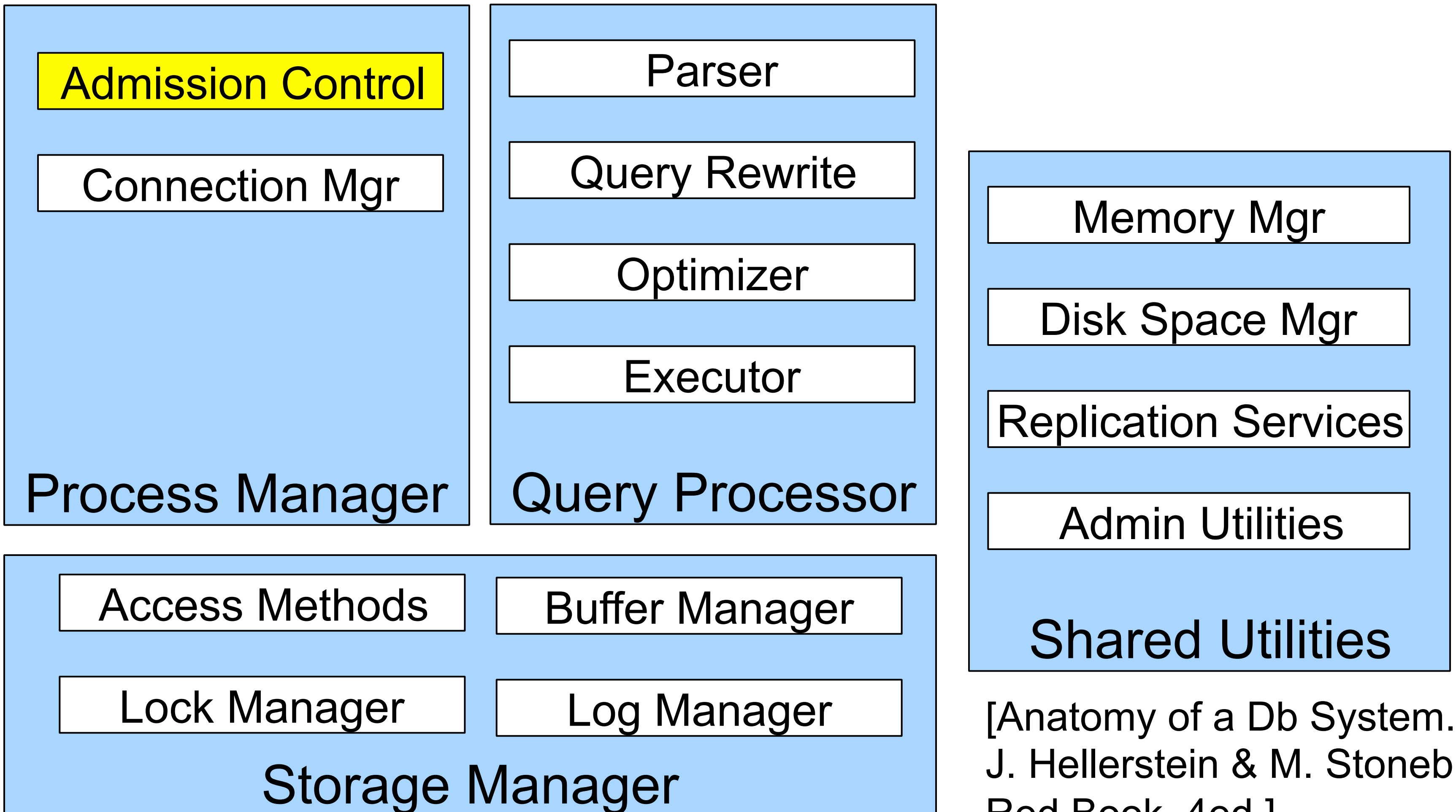
- **Drawbacks**
  - Replicating a good deal of OS logic
  - Need to manage thread state, scheduling, and task switching

- **How to map DBMS threads onto OS threads or processes?**
  - Rule of thumb: one OS-provided dispatchable unit per physical device
  - See page 9 and 10 of Hellerstein and Stonebraker's paper

Commercial Systems

- Oracle
  - Unix default: process-per-user mode
  - Unix: DBMS threads multiplexed across OS processes
  - Windows: DBMS threads multiplexed across OS threads
- IBM DB2
  - Unix: process-per-user mode
  - Windows: OS thread-per-user
- SQL Server
  - Windows default: OS thread-per-user
  - Windows: DBMS threads multiplexed across OS threads

DBMS Architecture



[Anatomy of a Db System.
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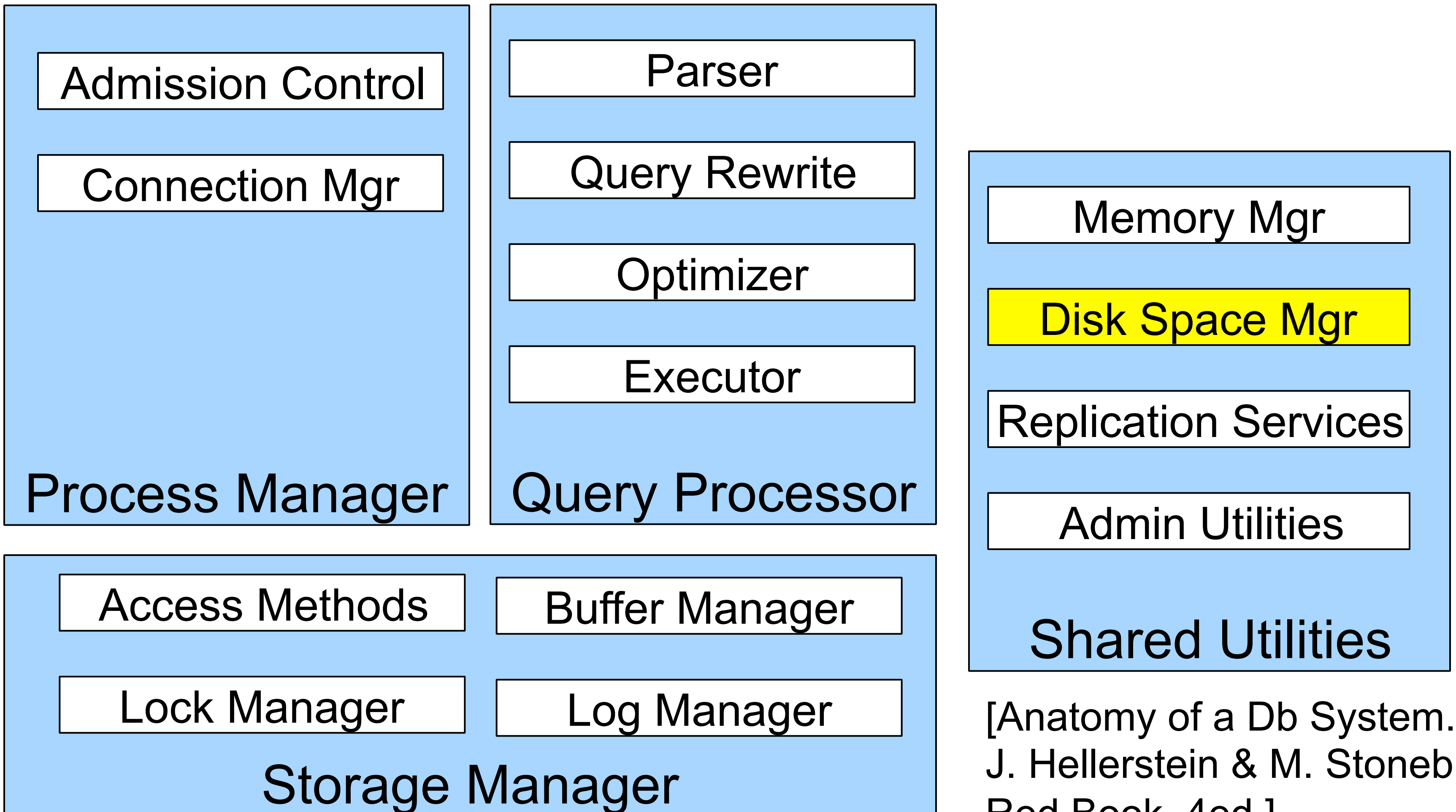
Admission Control

- Why does a DBMS need admission control?
  - To avoid thrashing and provide “graceful degradation” under load
- When does DBMS perform admission control?
  - In the dispatcher process: want to drop clients as early as possible to avoid wasting resources on incomplete requests
    - This type of admission control can also be implemented before the request reaches the DBMS (e.g., application server or web server)
  - Before query execution: delay queries to avoid thrashing
    - Can make decisions based on estimated resource needs for a query

DBMS Architecture



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Storage Model

- **Problem**: DBMS needs spatial and temporal control over storage
  - Spatial control for performance
  - Temporal control for correctness and performance

Alternatives

- **Use “raw” disk device interface directly**
  - Interact directly with device drivers for the disks
- **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”

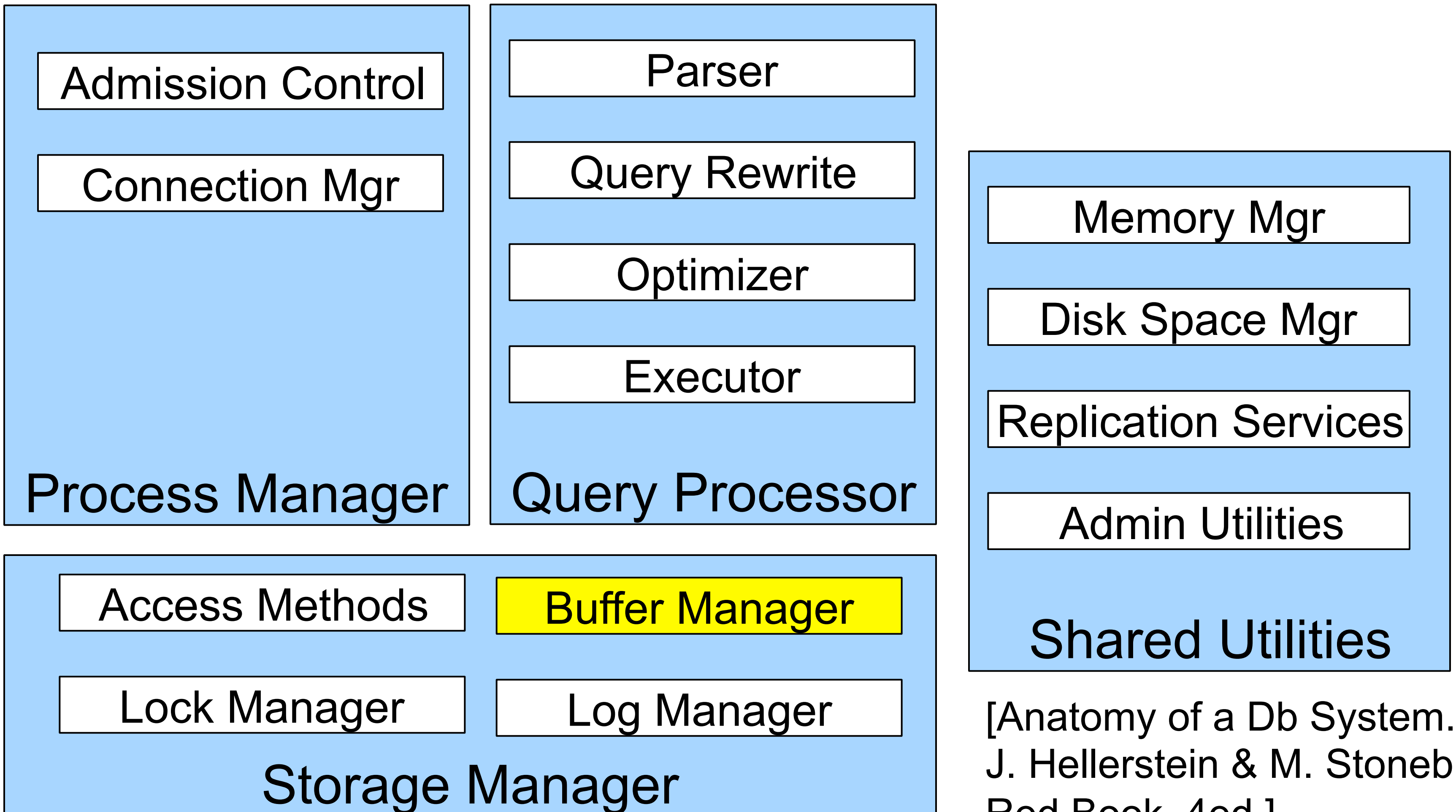
Spatial Control Using OS Files

- **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

DBMS Architecture



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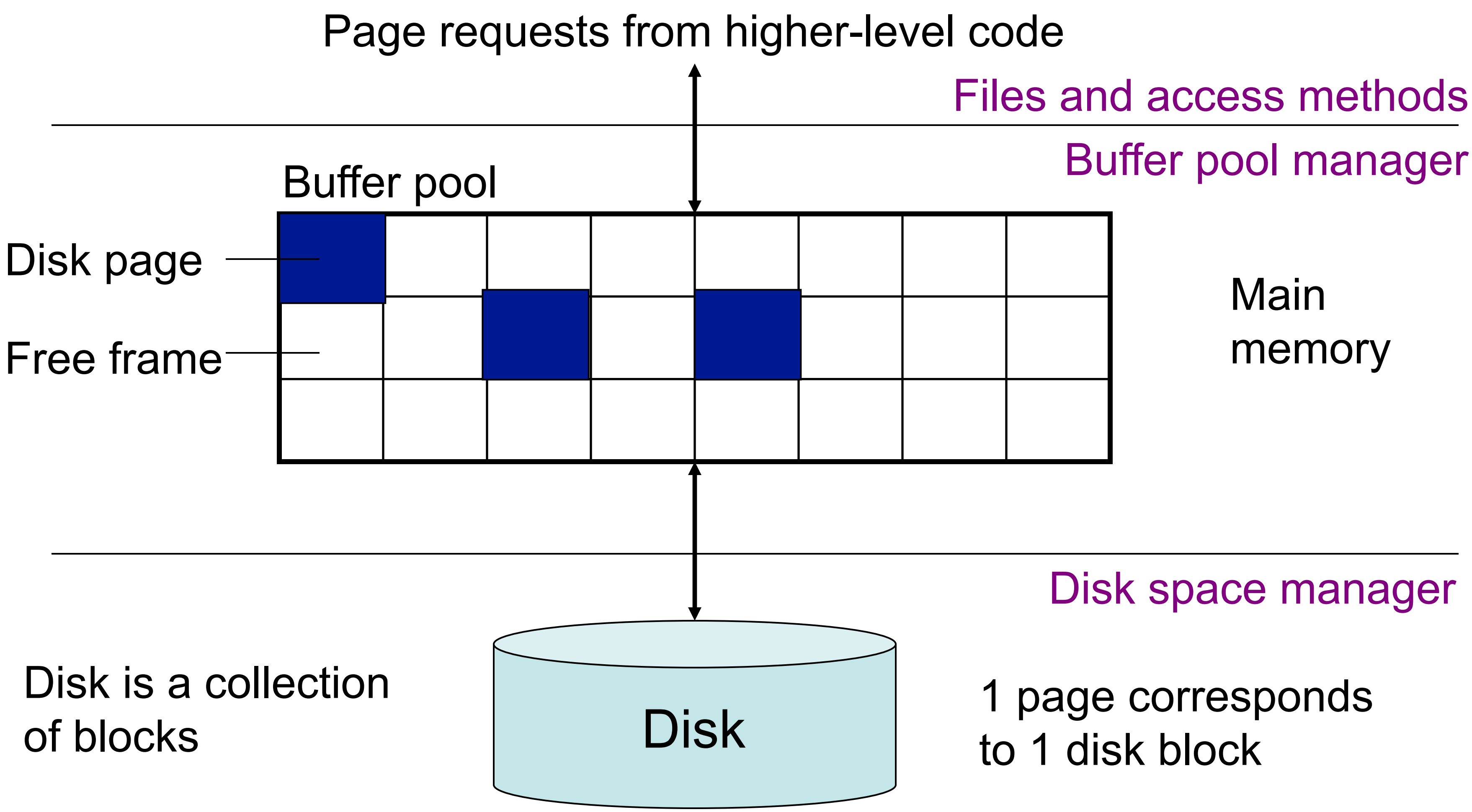
Temporal Control
Buffer Manager

- Correctness problems
  - DBMS needs to control when data is written to disk in order to provide **transactional semantics** (we will study transactions later)
  - OS buffering can **delay writes**, causing problems when crashes occur

- Performance problems
  - OS optimizes buffer management for general workloads
  - DBMS understands its workload and can do better
  - Areas of possible optimizations
    - Page replacement policies
    - Read-ahead algorithms (physical vs logical)
    - Deciding when to flush tail of write-ahead log to disk

Buffer Manager

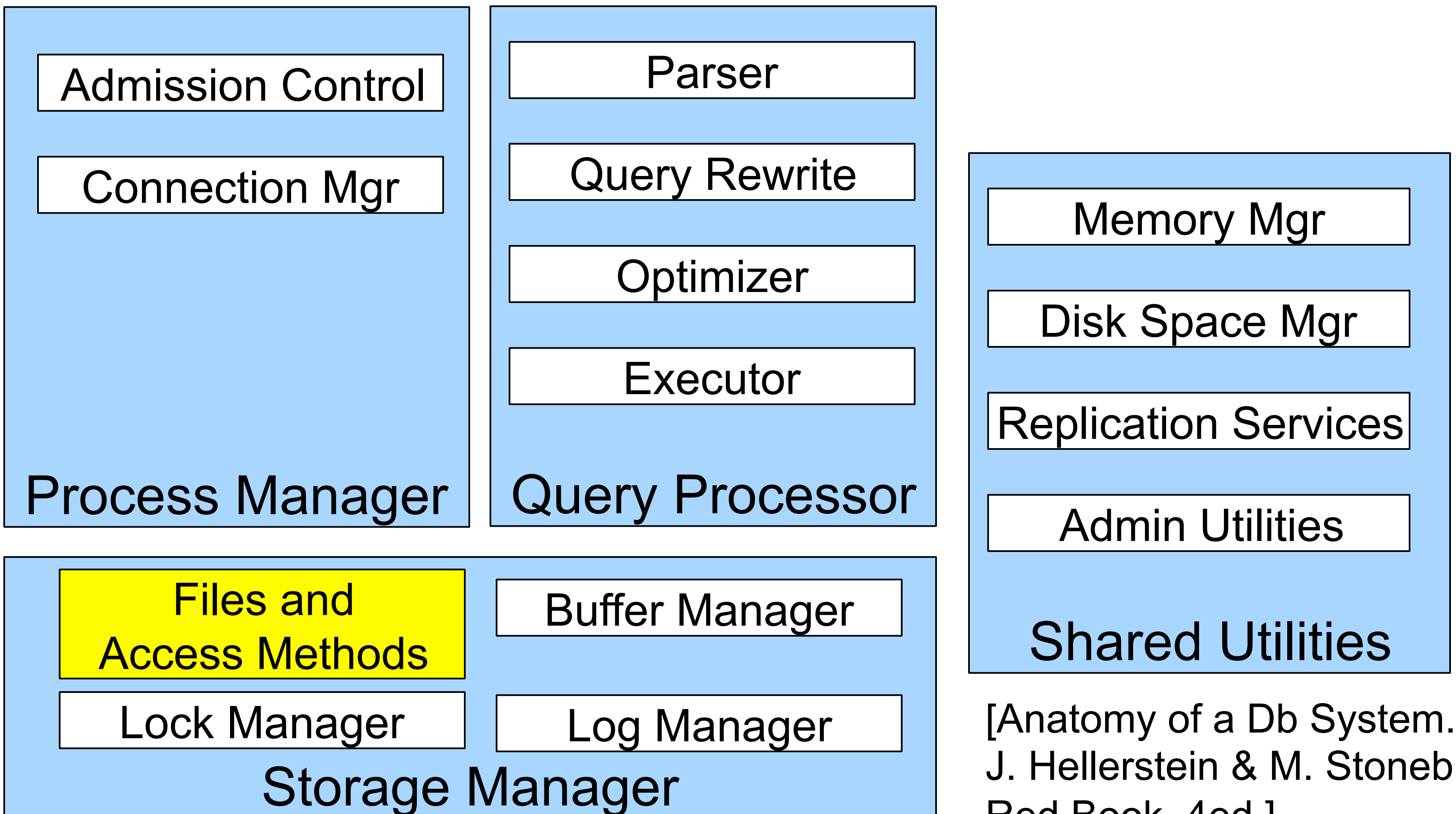


Commercial Systems

- DBMSs implement their own buffer pool managers

- Modern filesystems provide good support for DBMSs
  - Using large files provides good spatial control
  - Using interfaces like the mmap suite
    - Provides good temporal control
    - Helps avoid double-buffering at DBMS and OS levels

DBMS Architecture



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Access Methods

- 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

Data Storage

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

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

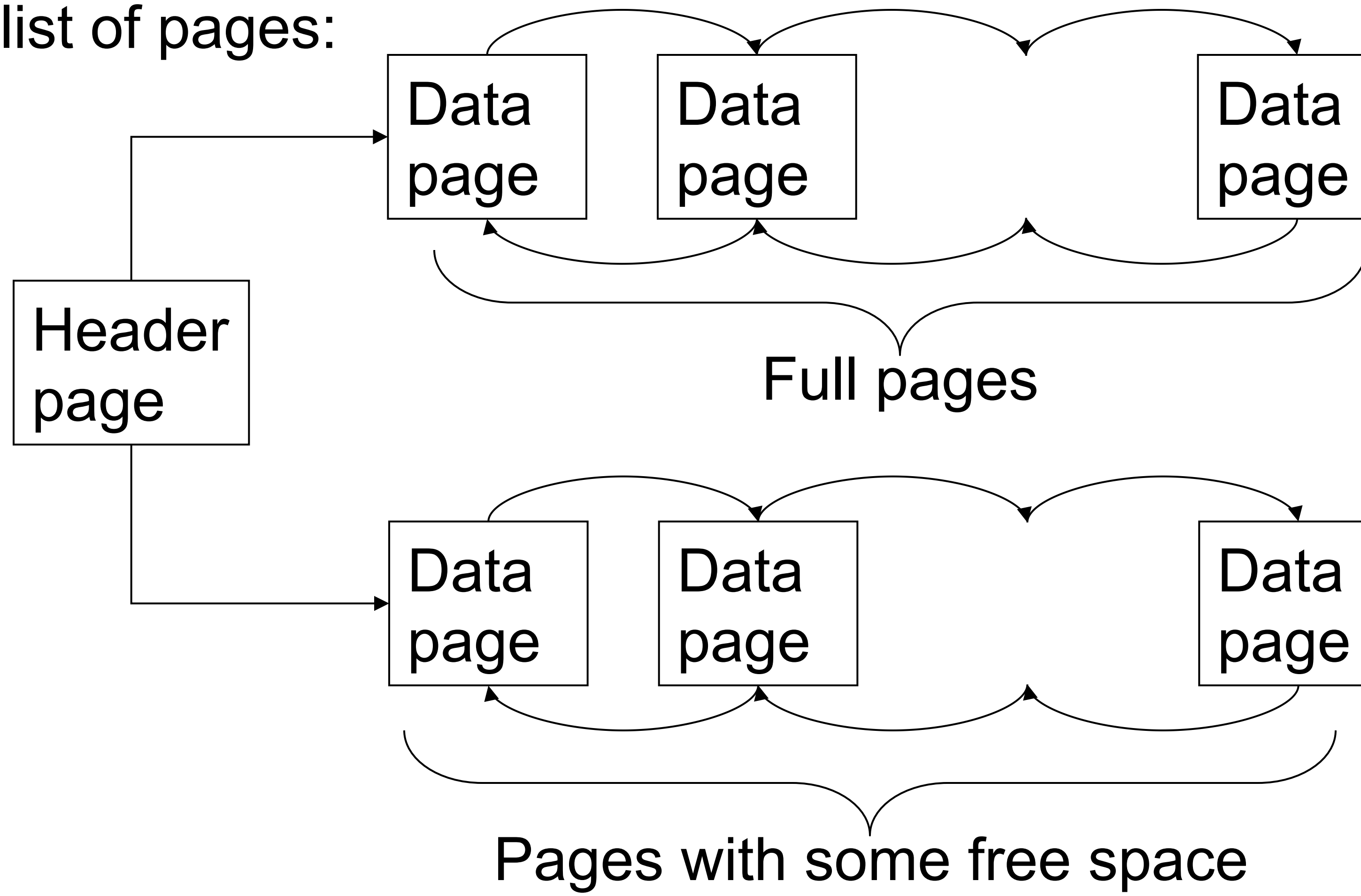
- Simplest approach: **heap file** (unordered)

Heap File Operations

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

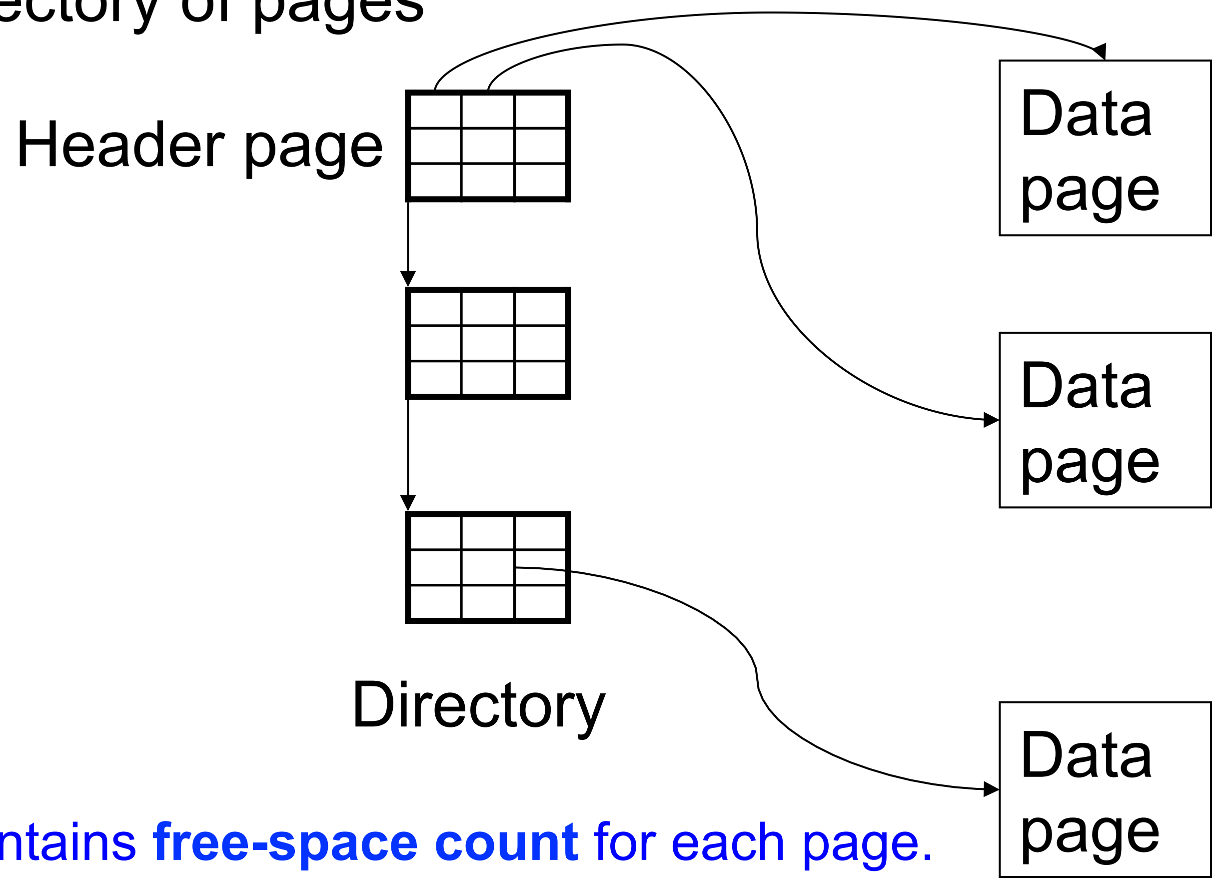
Heap File Implementation 1

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

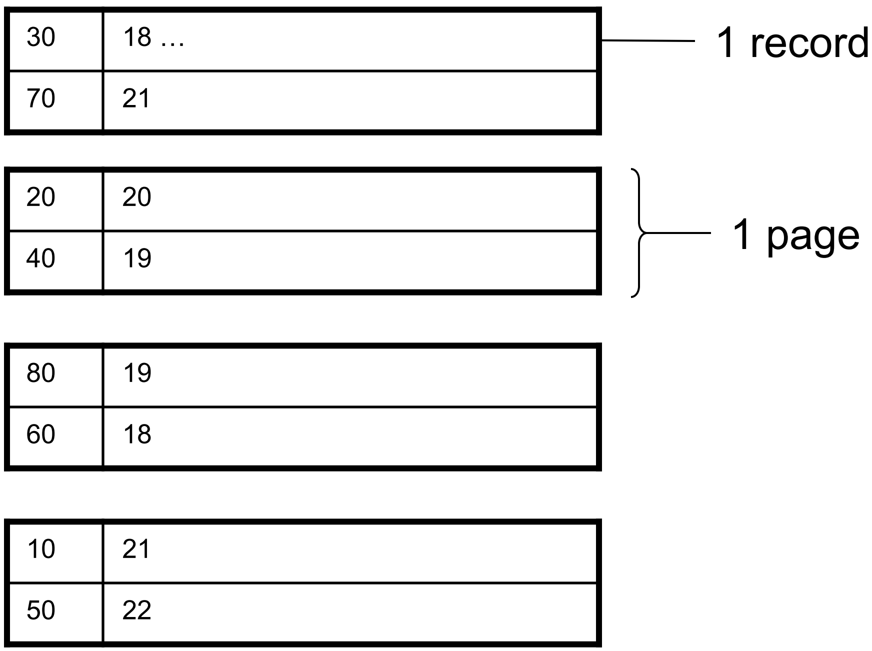
Types of Files

- Heap file (what we discussed so far)
  - Unordered
- Sorted file (also called sequential file)
- Clustered file (aka indexed file)

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?

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

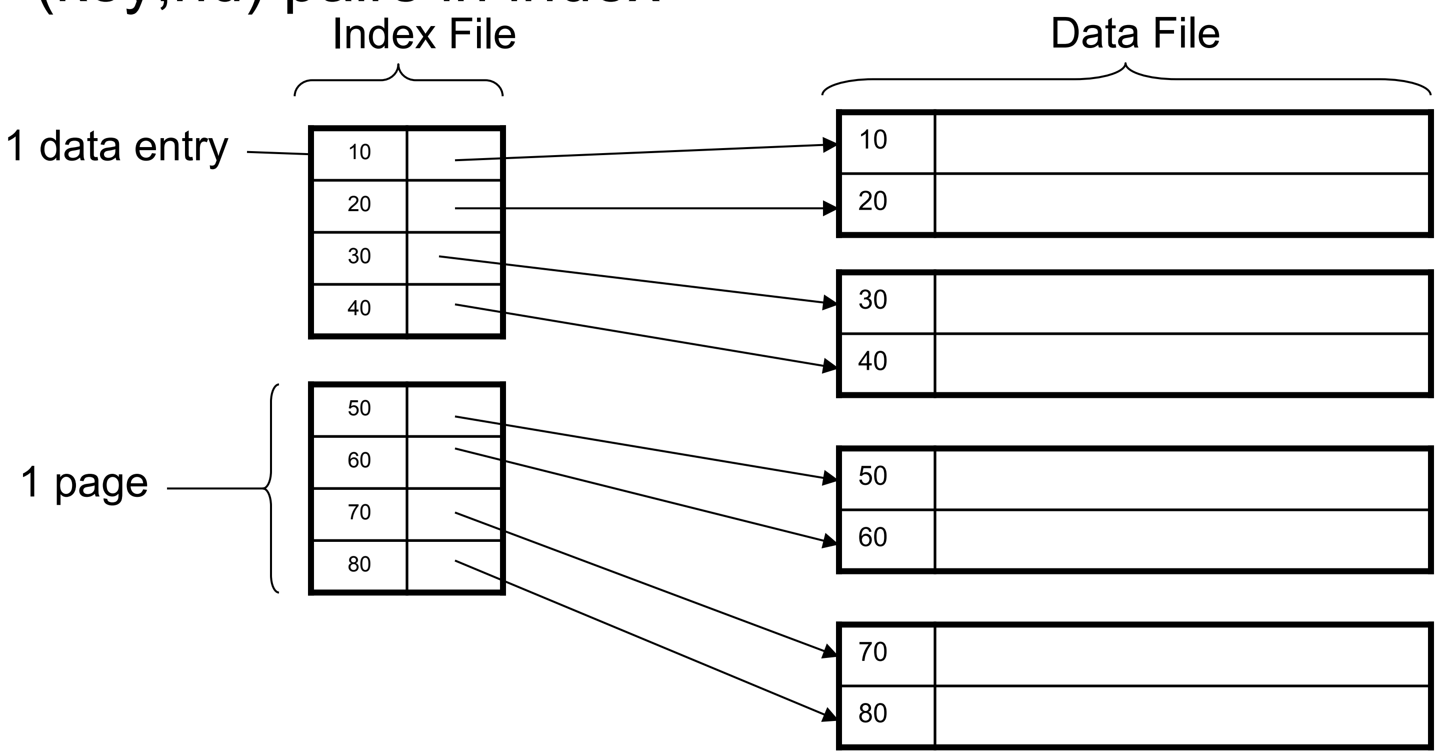
- **Search key** = can be any set of fields
  - not the same as the primary key, nor a key

- **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**
    - Called: “indexed file organization”
  - (k, RID)
  - (k, list-of-RIDs)

Primary Index

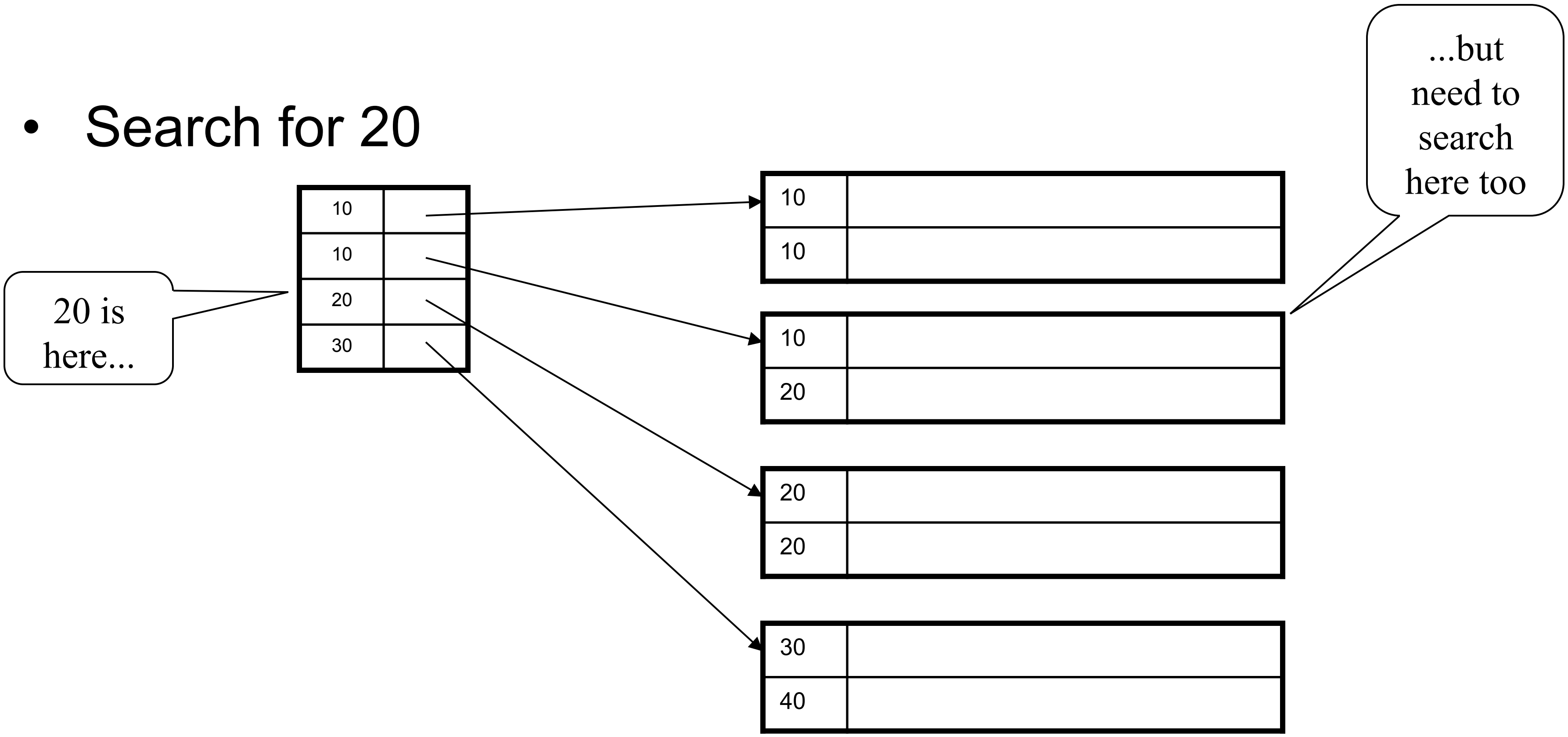
- Primary index: determines location of indexed records
- *Dense* index: each record in data file is pointed to by a (key,rid) pairs in index



Primary Index with Duplicate Keys

- *Sparse* index: pointer to lowest search key on each page:

- Search for 20

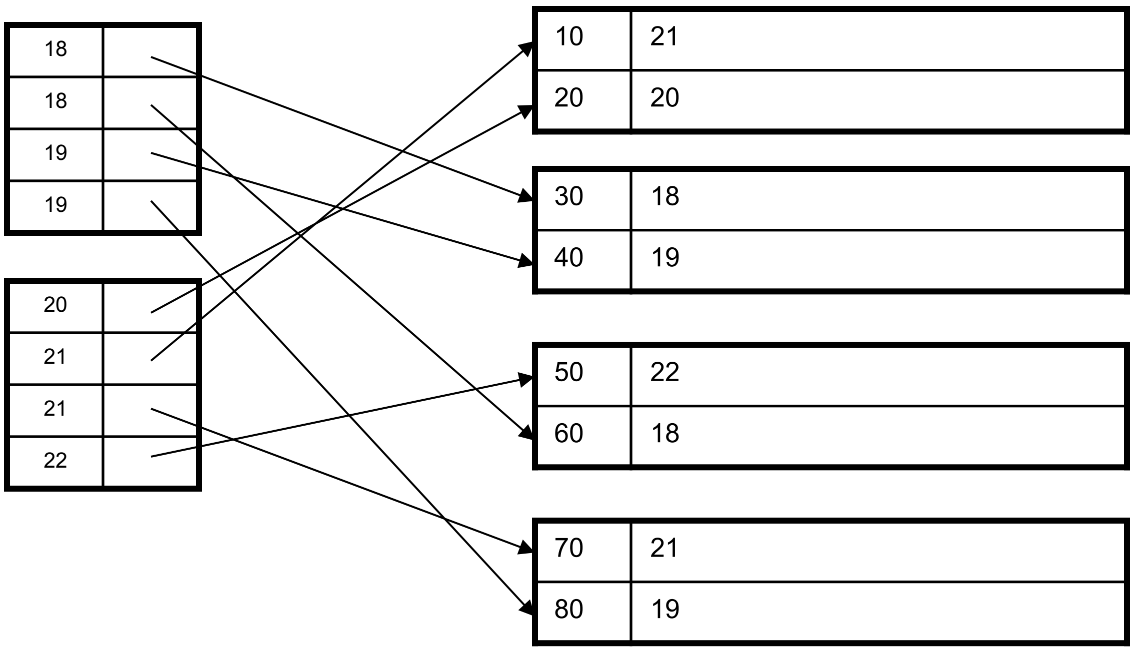


Primary Index Example

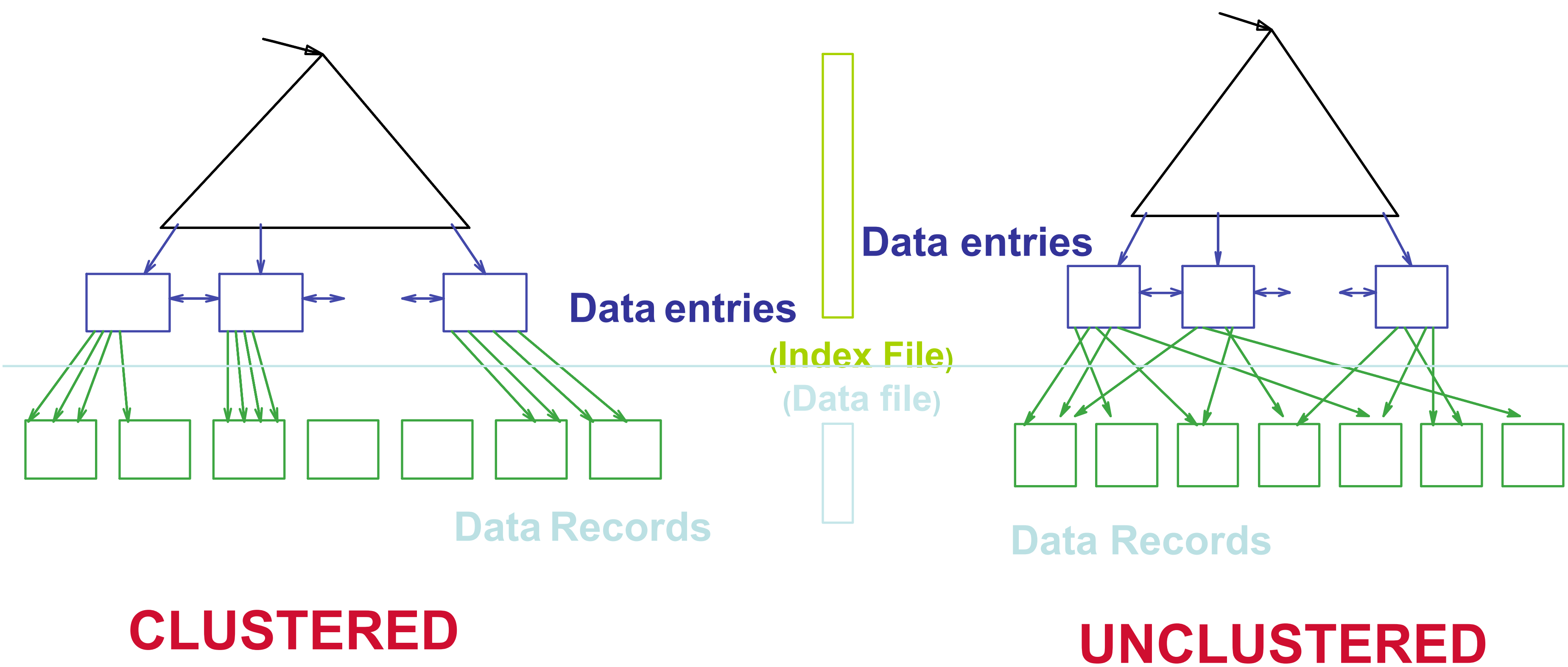
- Let's assume all pages of index fit in memory
- Find student whose sid is 80
  - Index (dense or sparse) points directly to the page
  - Only need to read 1 page from disk.
- Find all students older than 20
  - Must still read all 1,000 pages.
- How can we make *both* queries fast?

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

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 / …

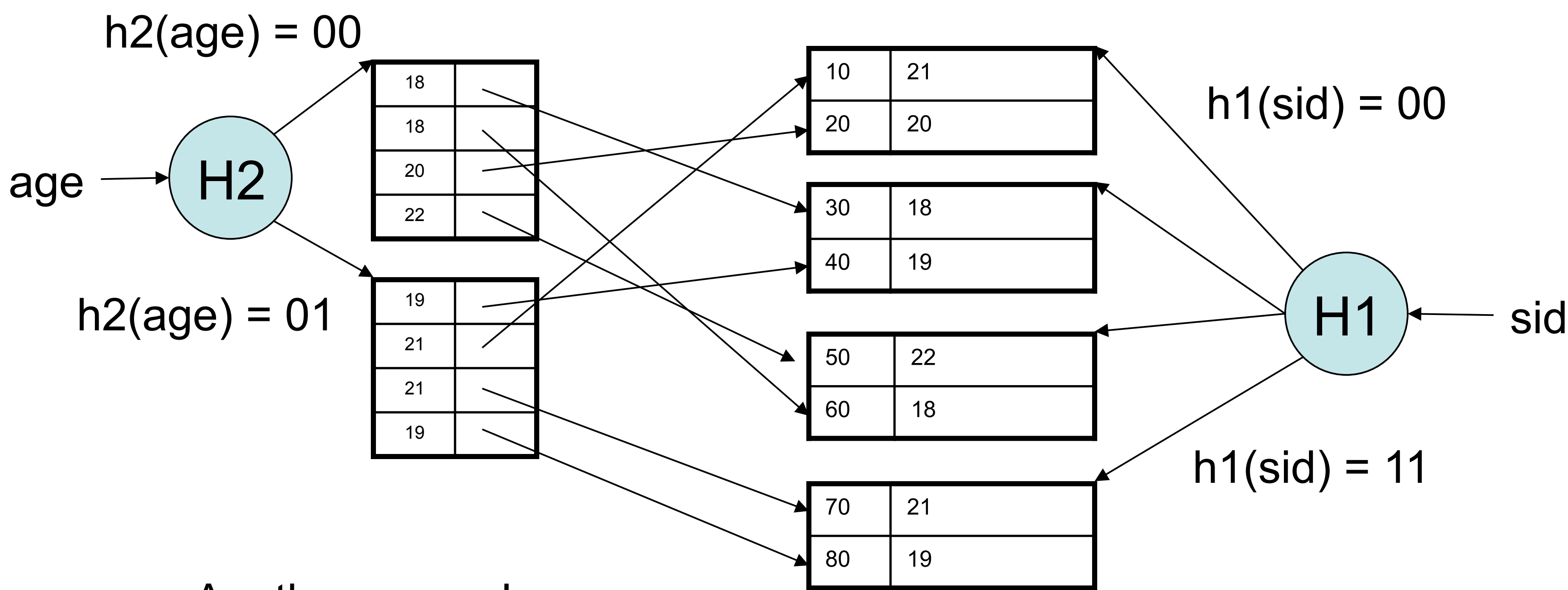
Large Indexes

- What if index does not fit in memory?

- Why not 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 and indexed-file organization

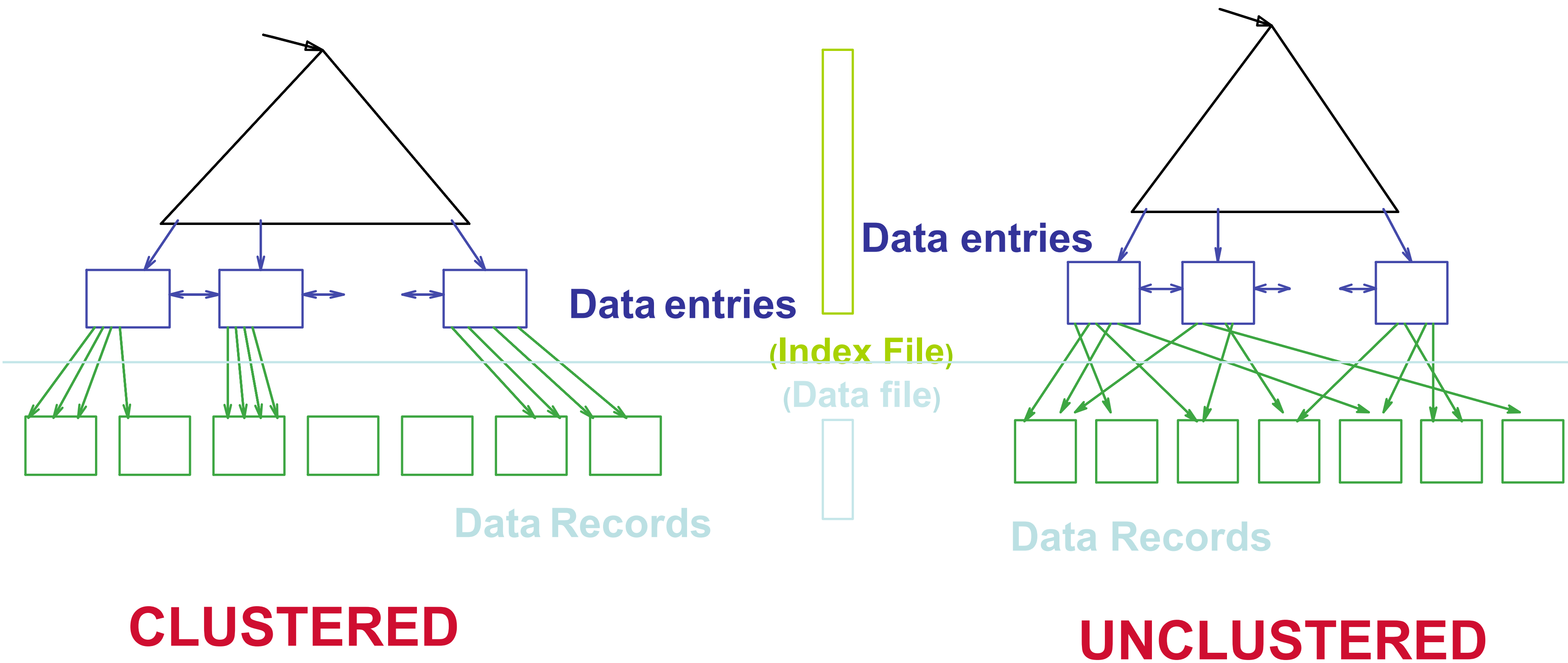
Tree-Based Index

- 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

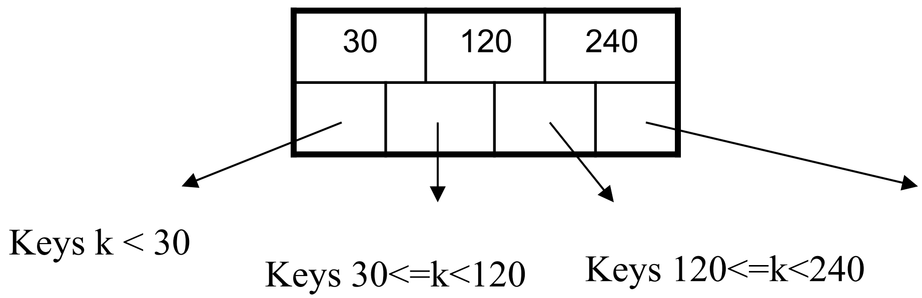
B+ Trees



Note: can also store data records directly as data entries

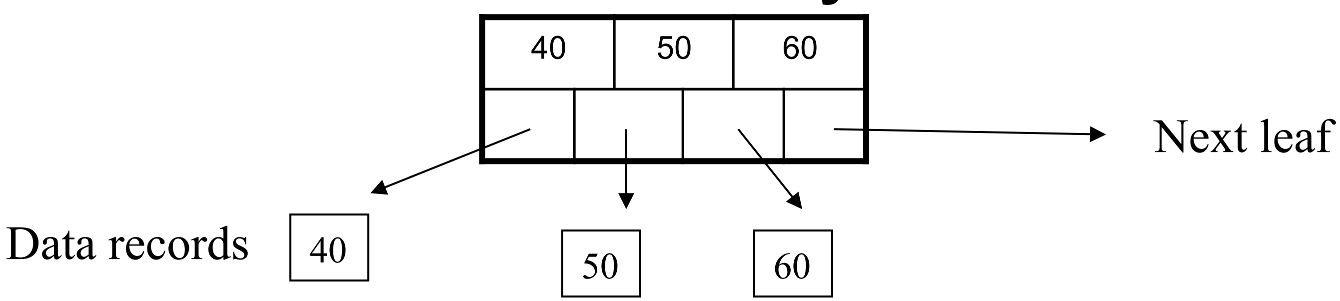
B+ Trees Basics

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



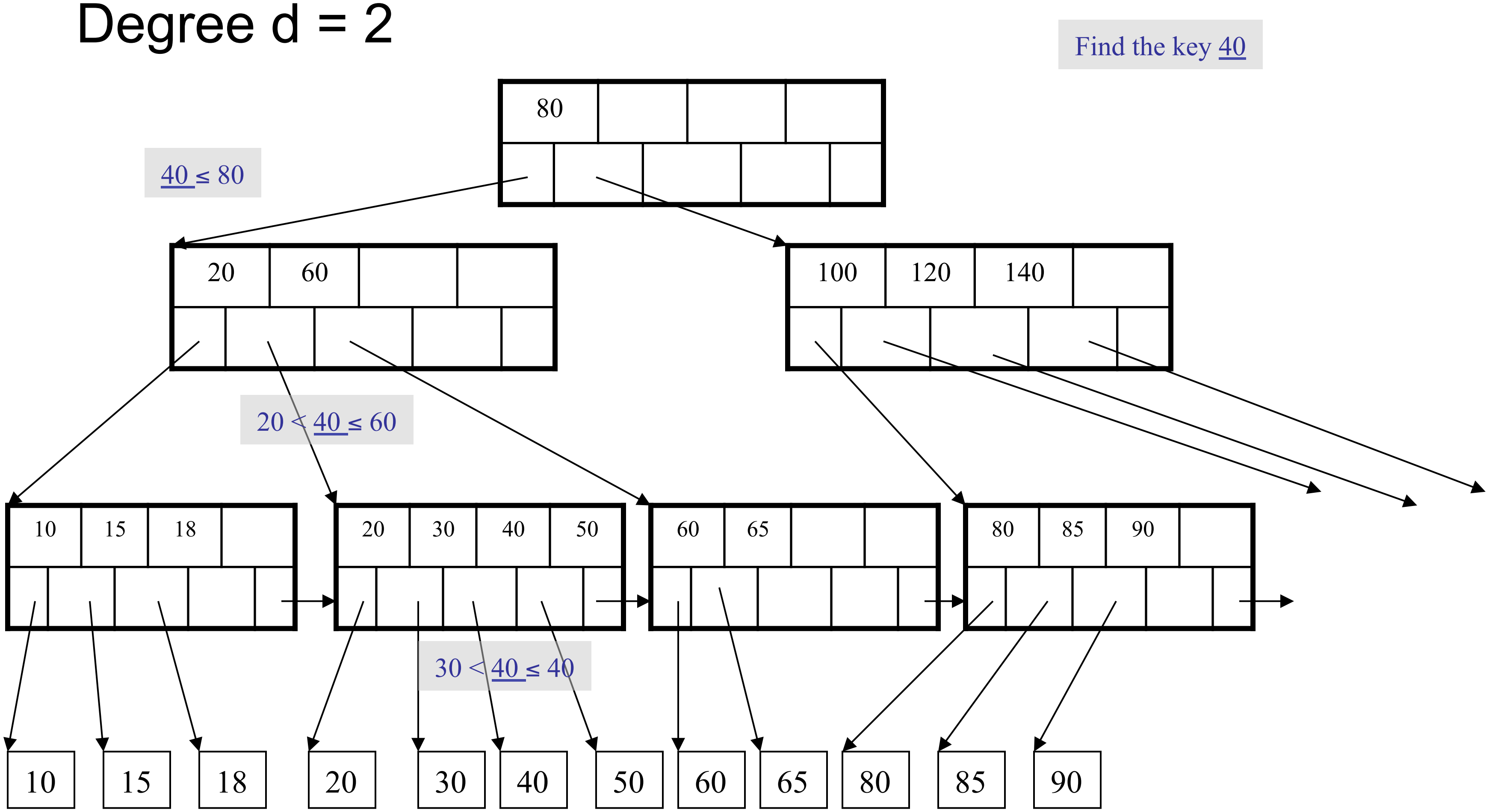
Each node also has **m+1 pointers**

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



B+ Tree Example

Degree 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

Index on Student(age)

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

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

B+ Tree Design

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

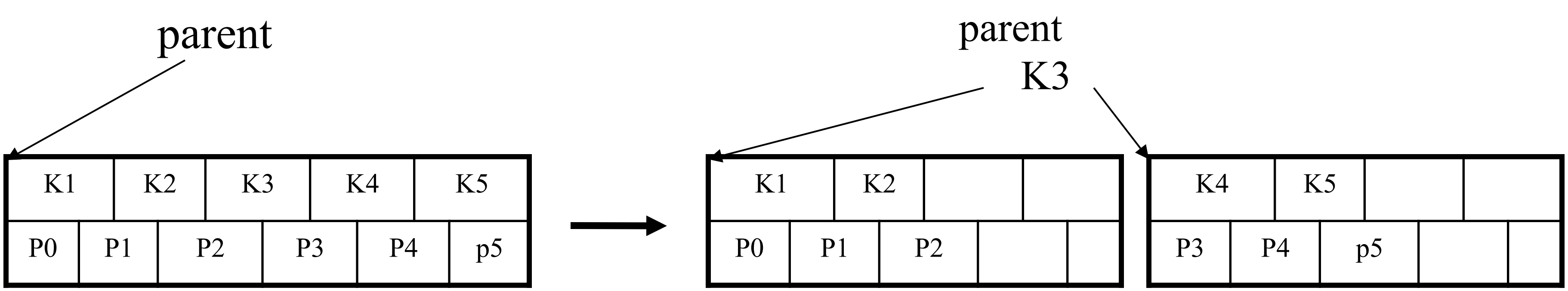
B+ Trees in Practice

- 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)

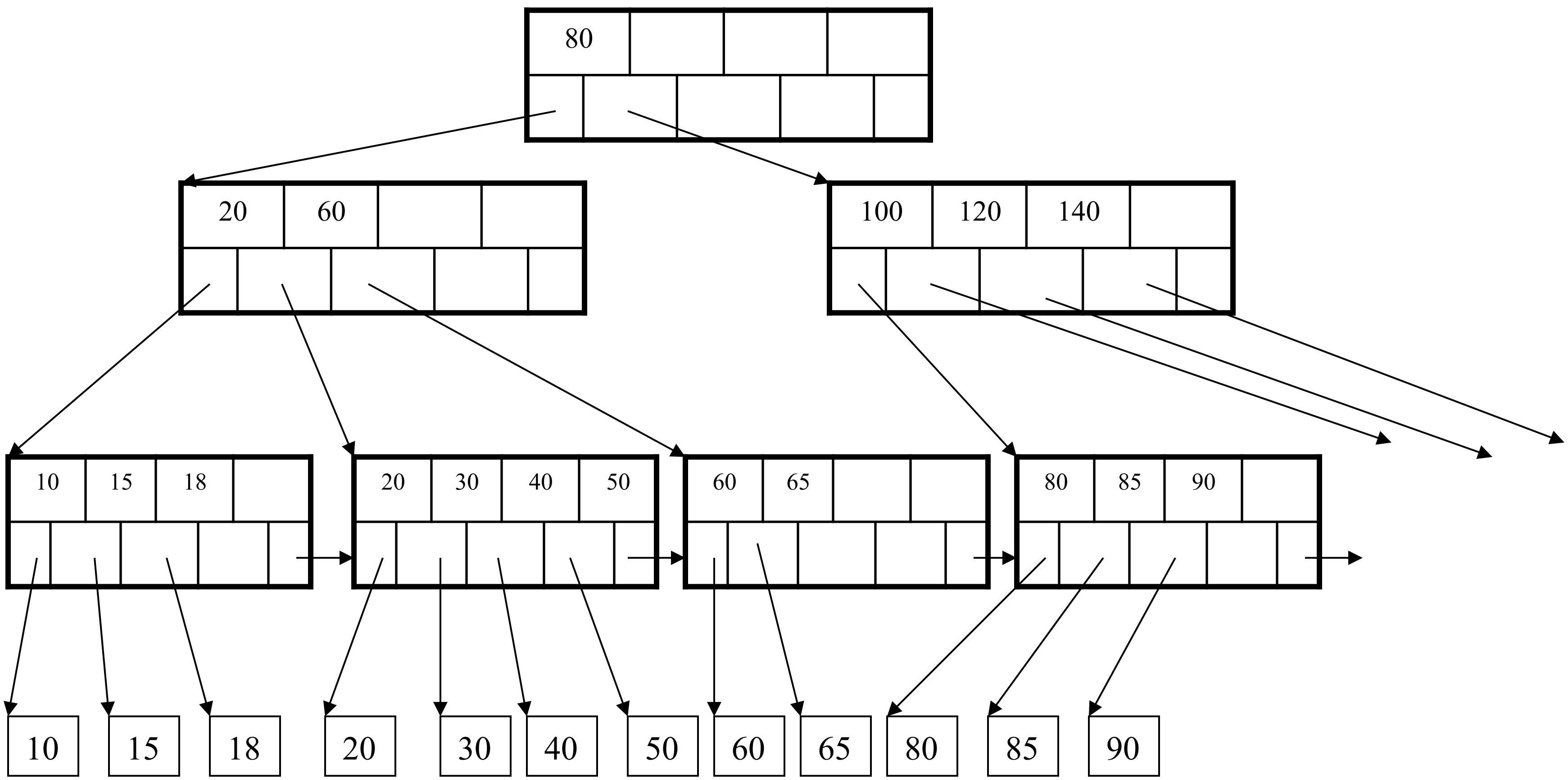
- Find leaf where K belongs, insert
- If no overflow (2d keys or less), halt
- If overflow (2d+1 keys), split node, insert in parent:



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

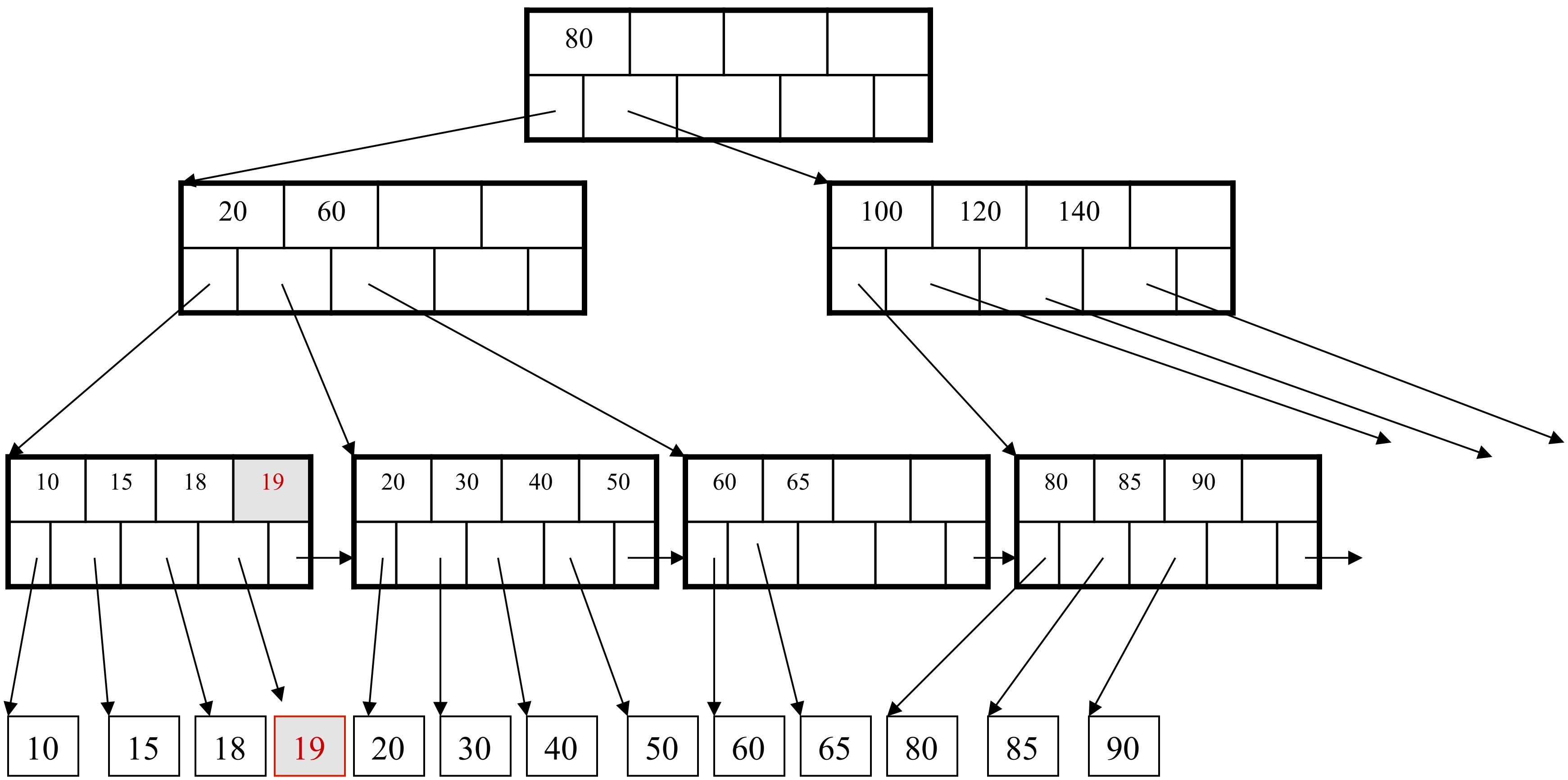
Insertion in a B+ Tree

Insert K=19



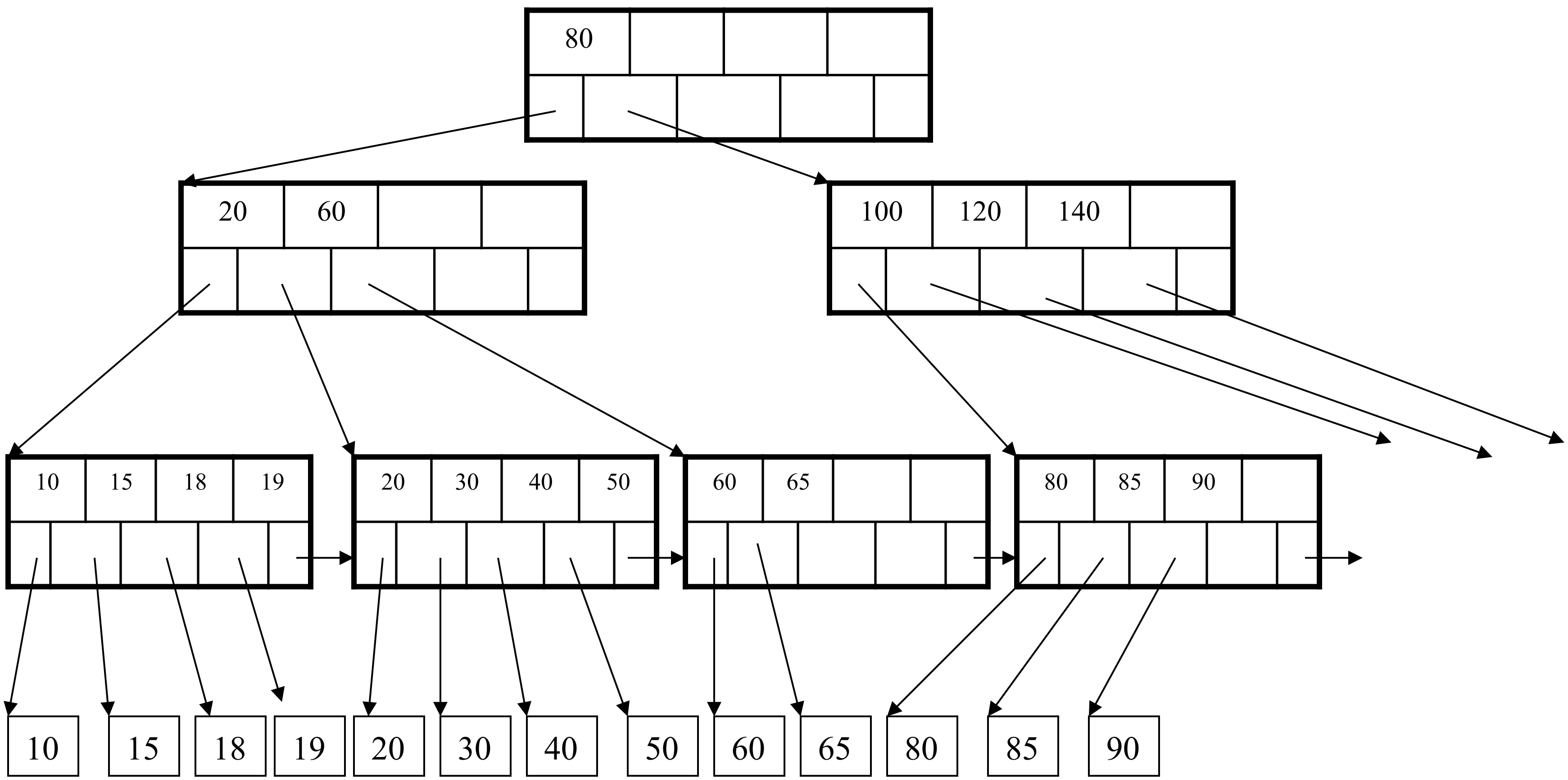
Insertion in a B+ Tree

After insertion



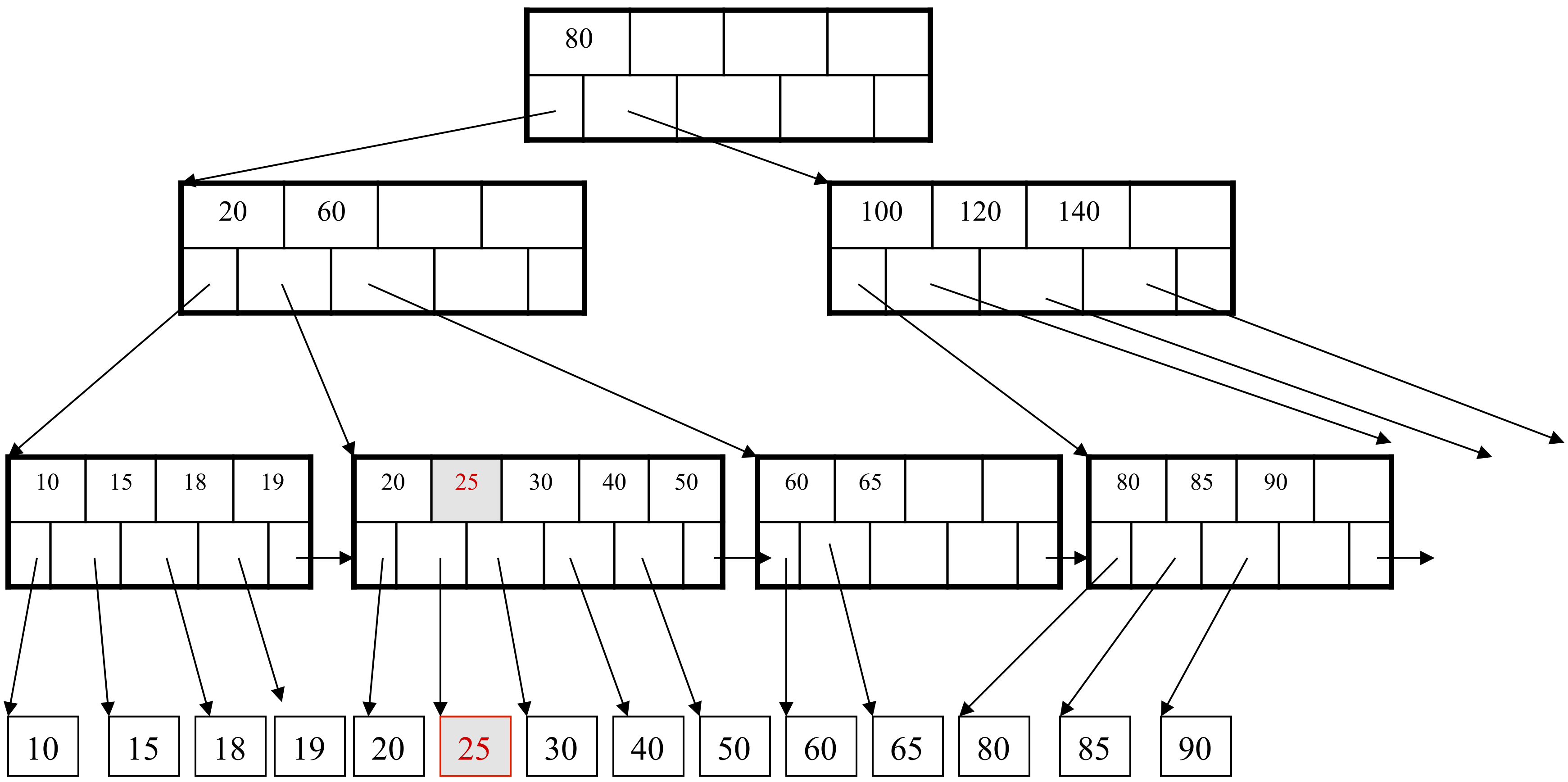
Insertion in a B+ Tree

Now insert 25



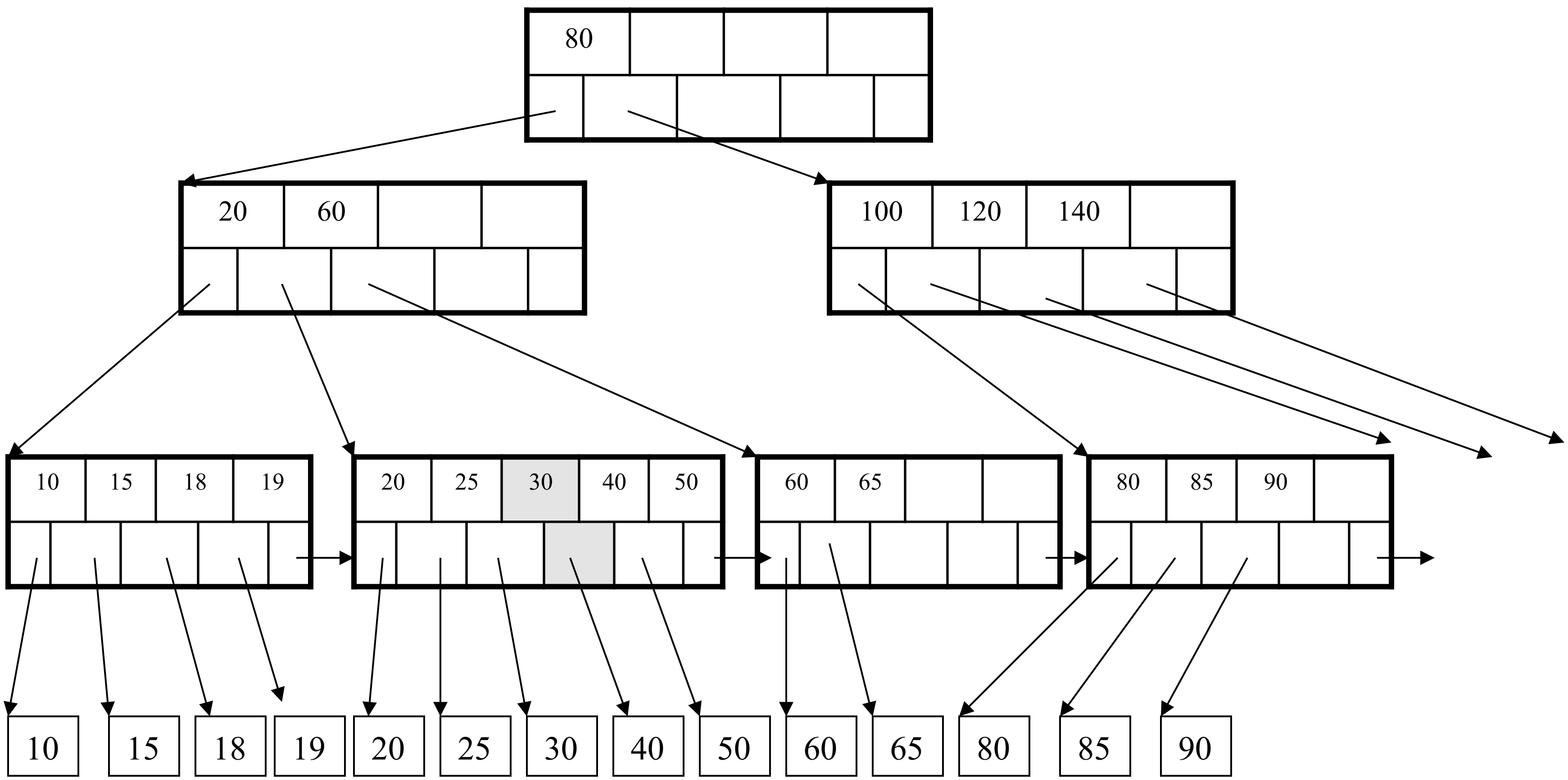
Insertion in a B+ Tree

After insertion



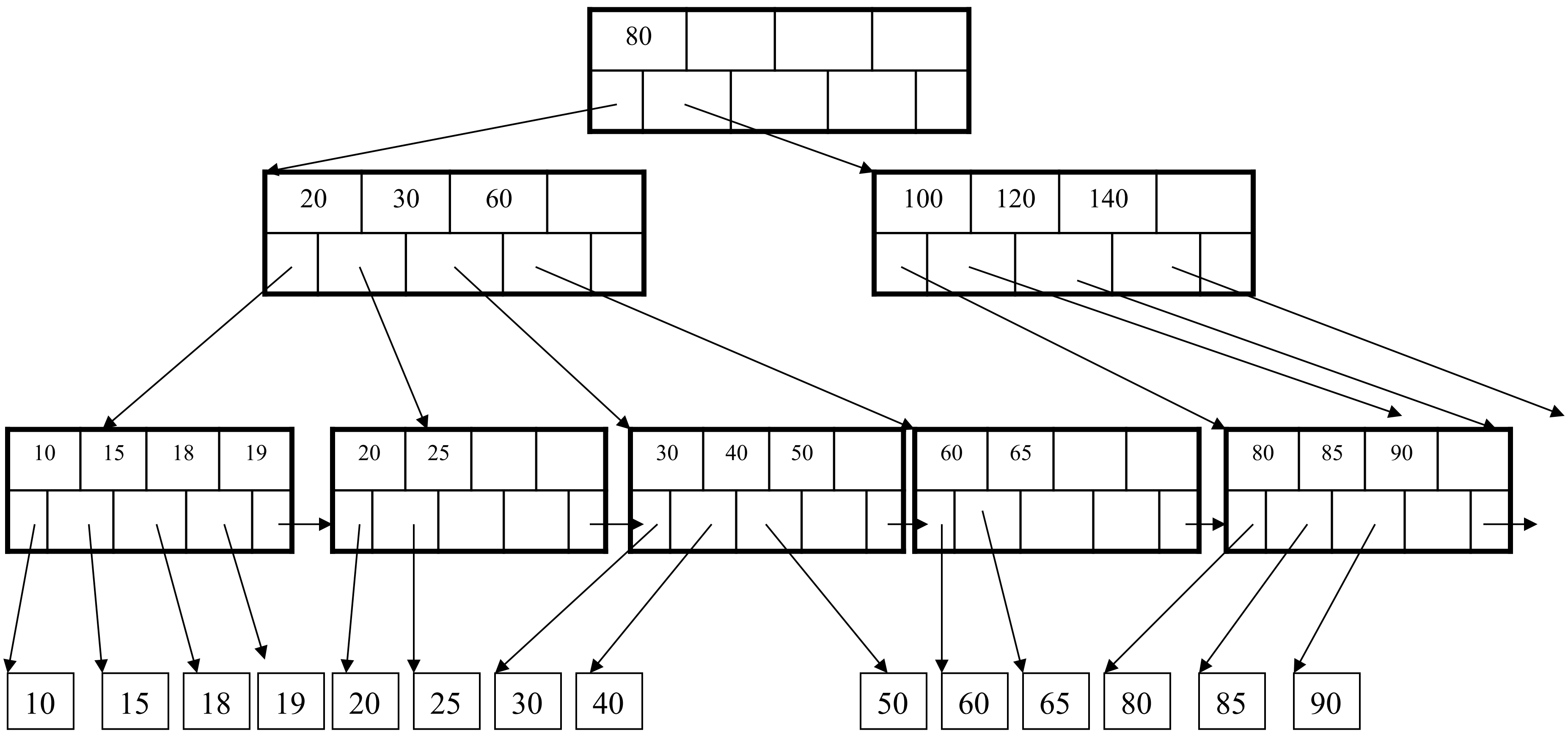
Insertion in a B+ Tree

But now have to split !



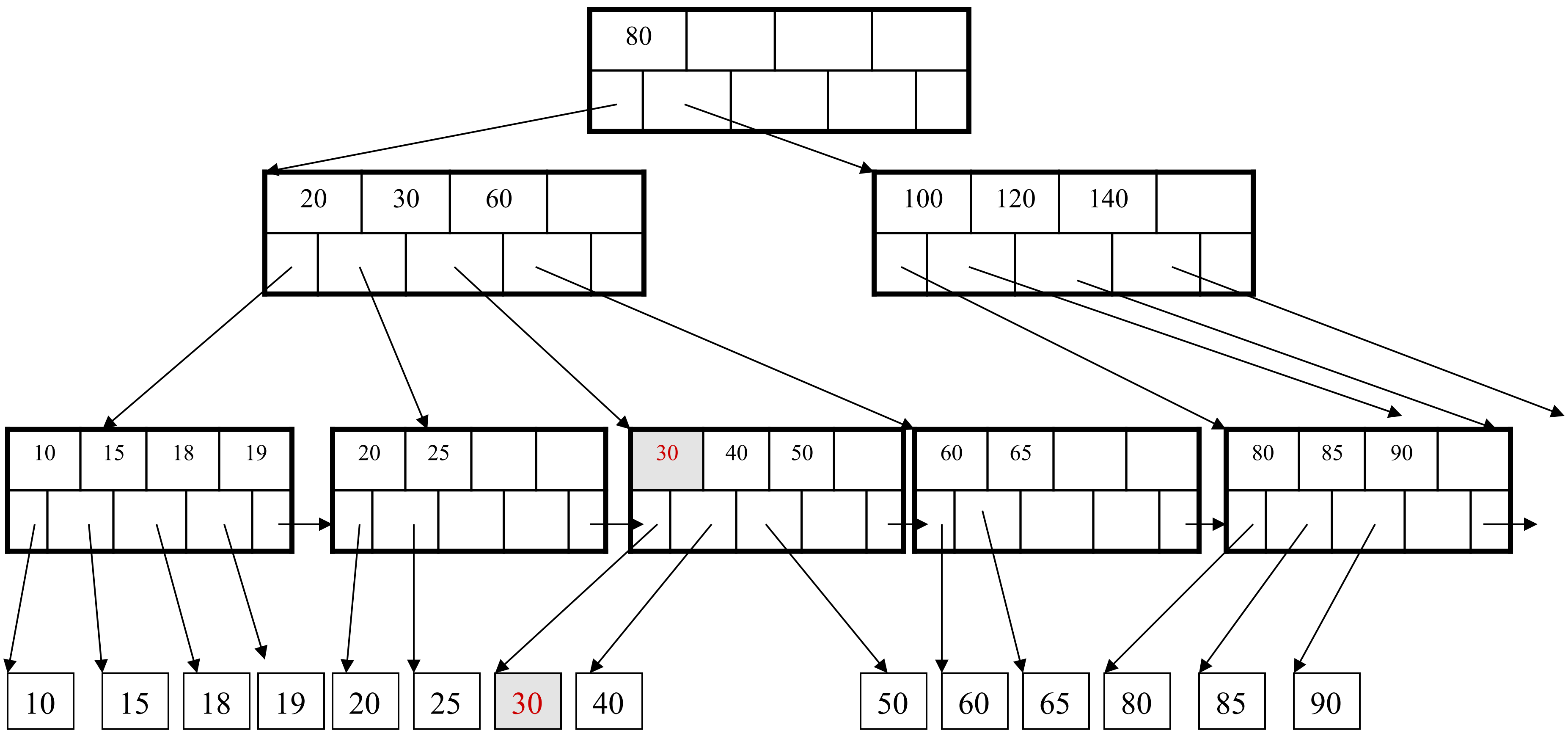
Insertion in a B+ Tree

After the split



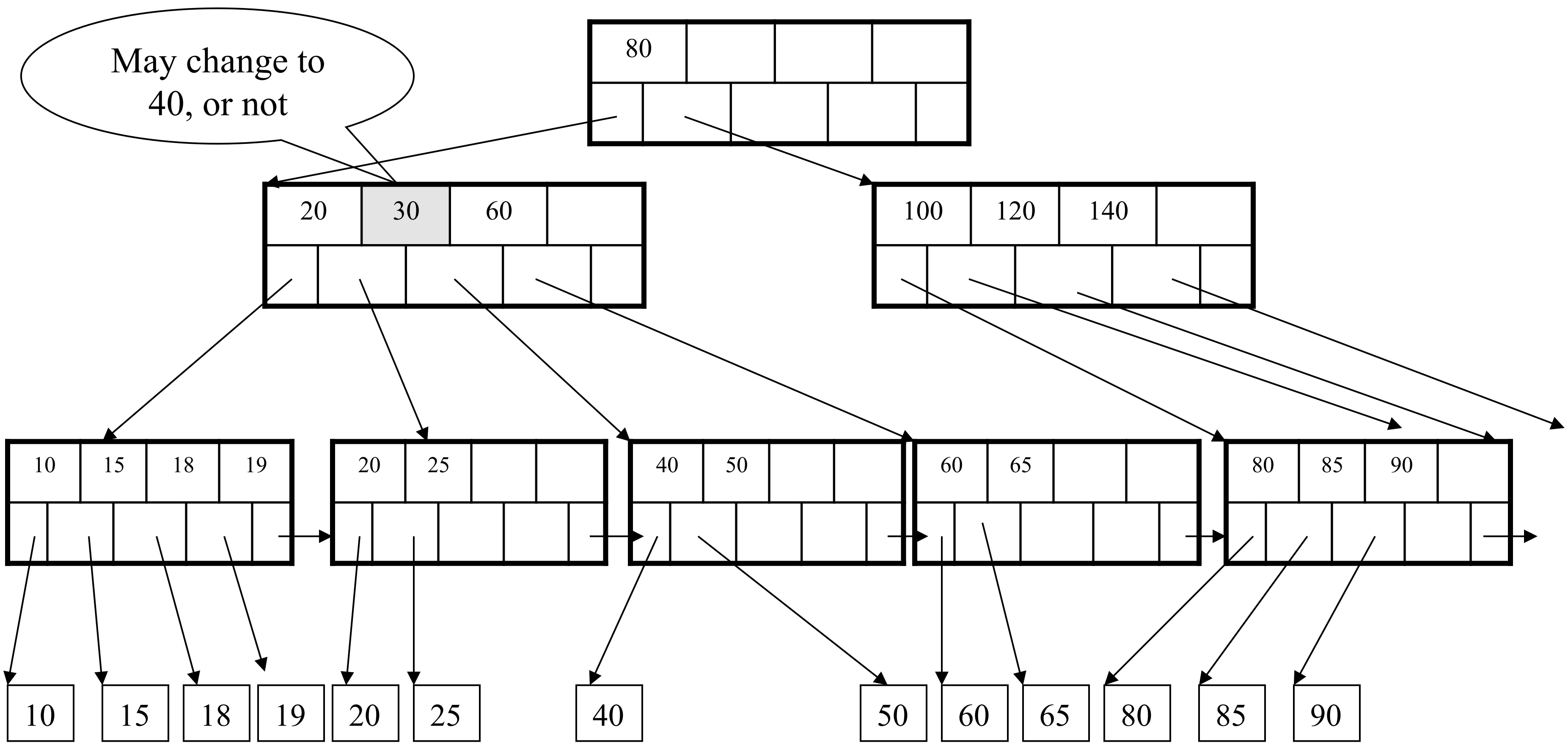
Deletion from a B+ Tree

Delete 30



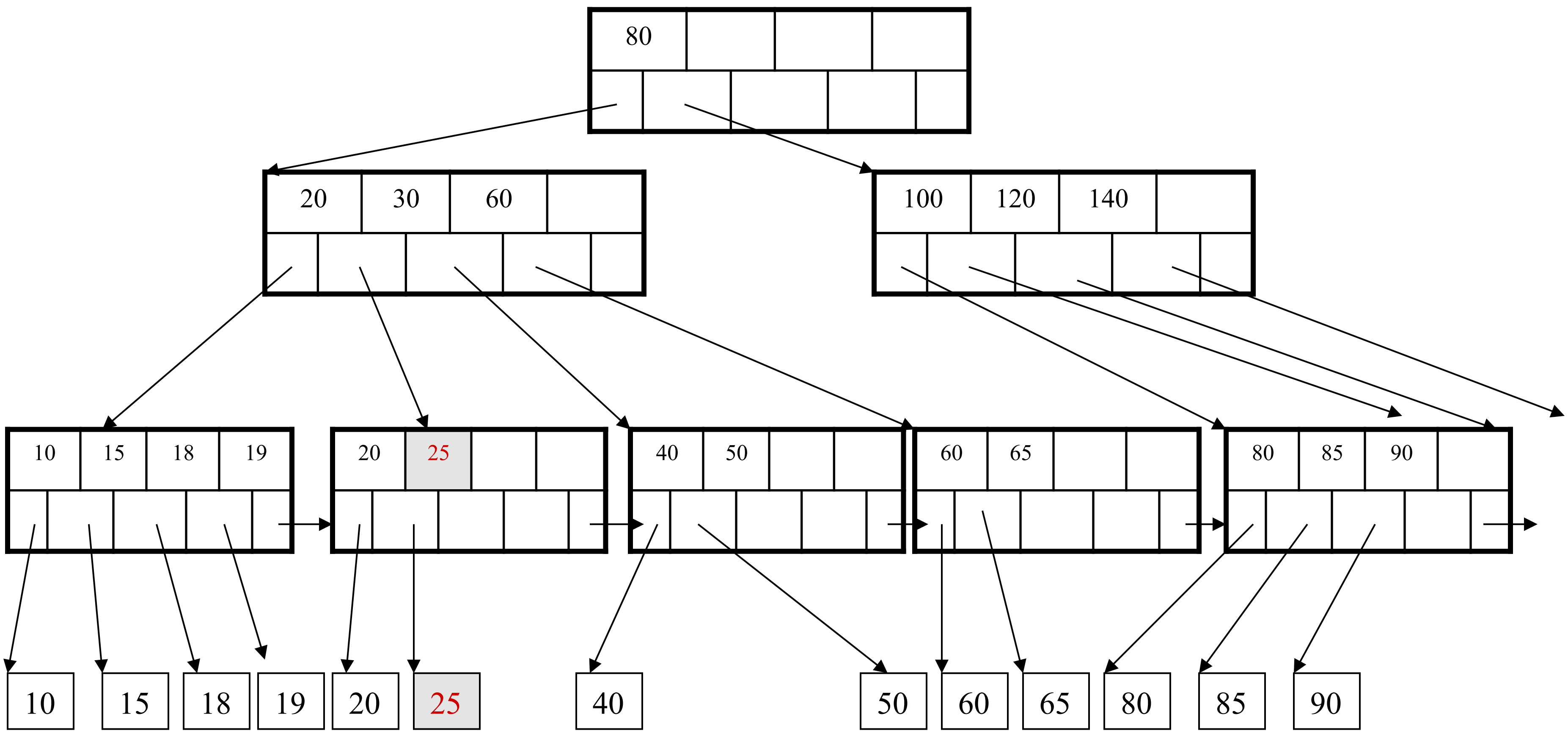
Deletion from a B+ Tree

After deleting 30



Deletion from a B+ Tree

Now delete 25

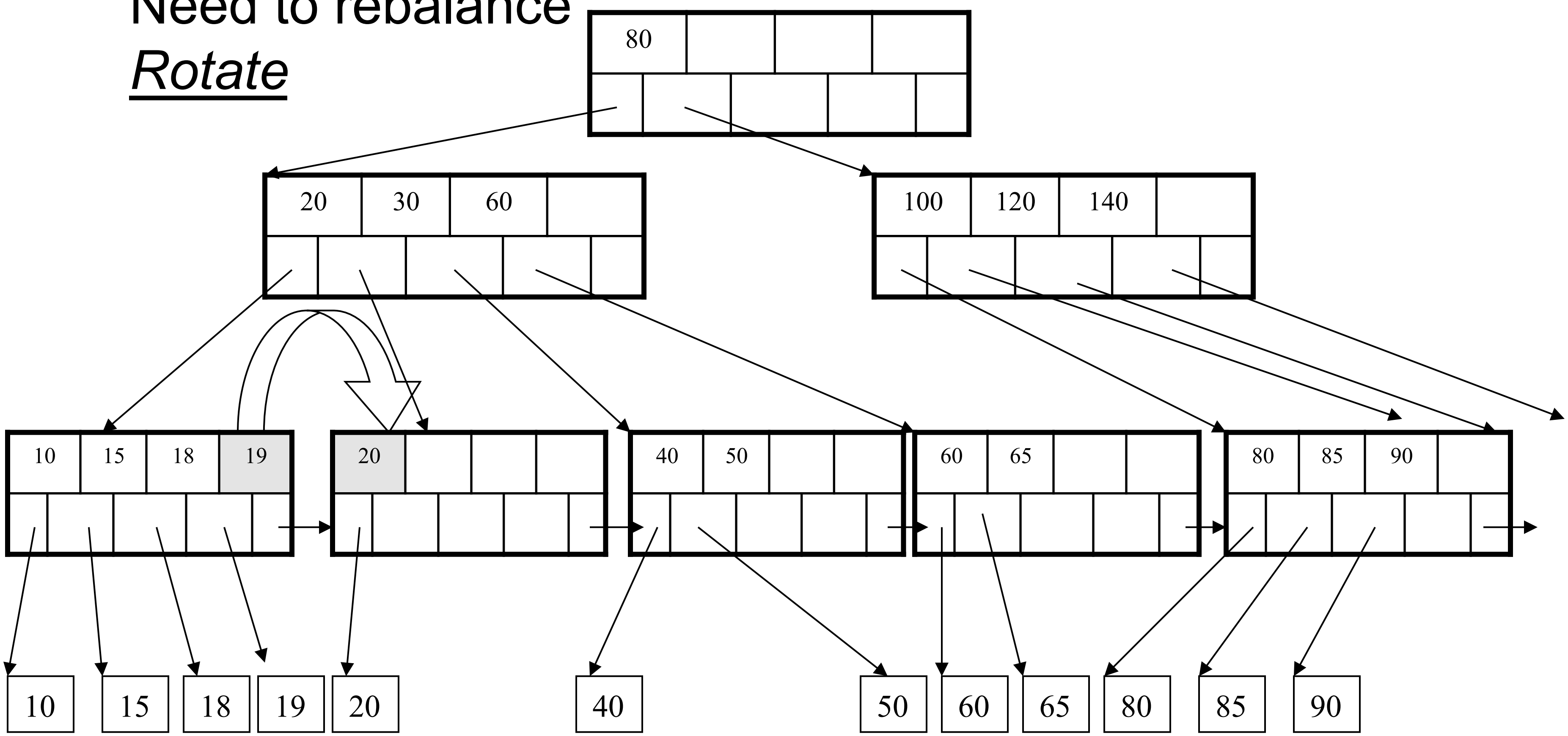


Deletion from a B+ Tree

After deleting 25

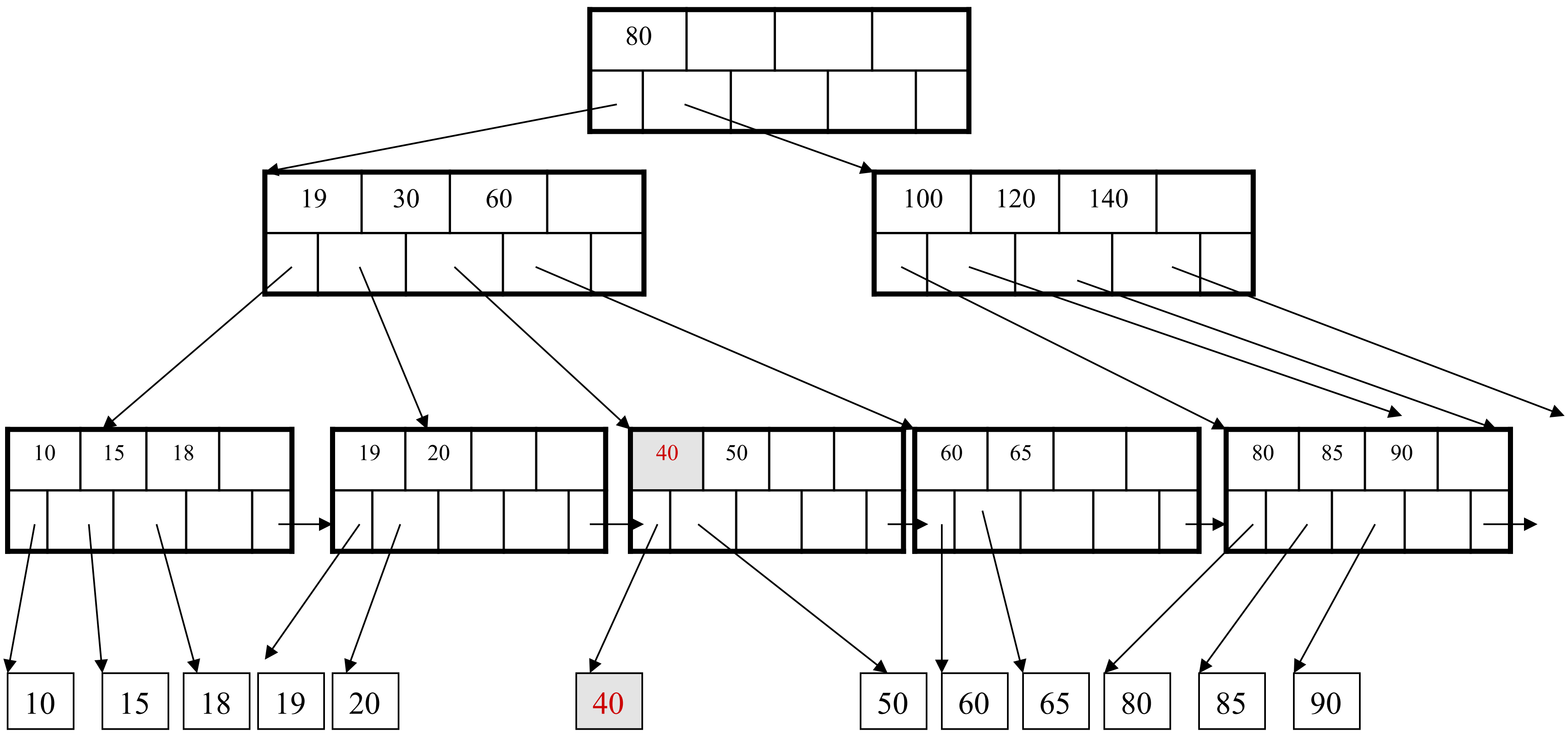
Need to rebalance

Rotate



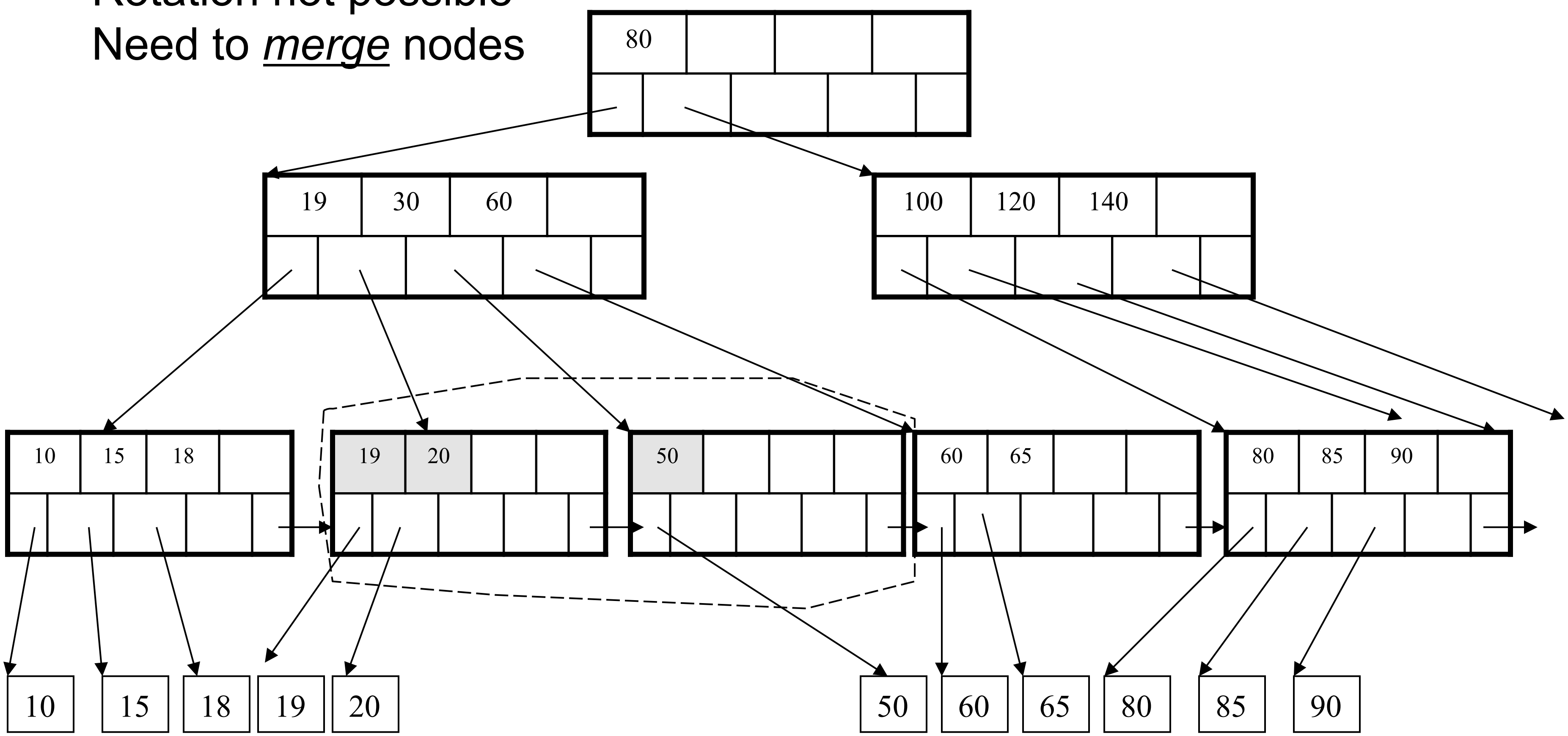
Deletion from a B+ Tree

Now delete 40



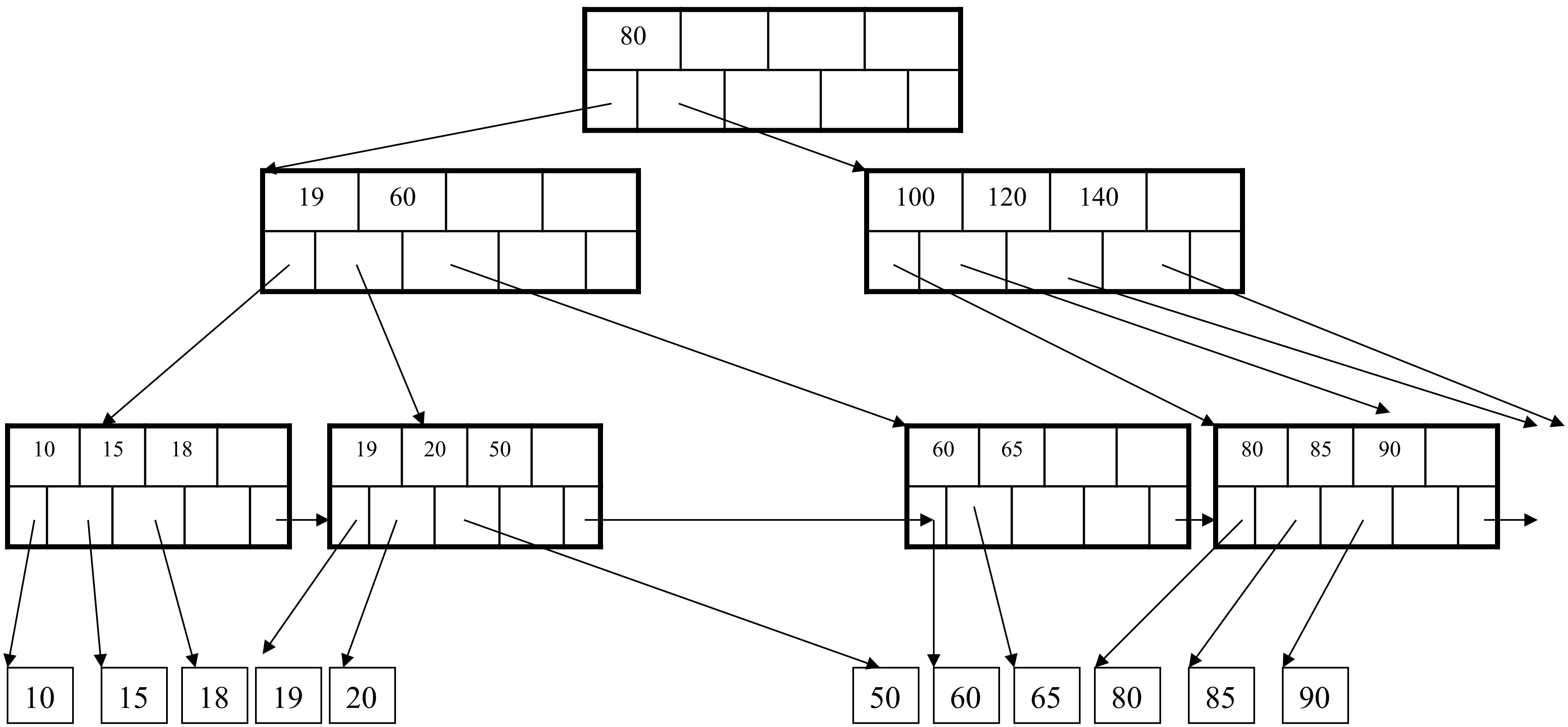
Deletion from a B+ Tree

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

Indexes in Postgres

```
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

Index Selection Problem 1

V(M, N, P)

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N=?
```

100 queries:

```
SELECT *
FROM V
WHERE P=?
```

Which indexes should we create?

Index Selection Problem 1

V(M, N, P)

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N=?
```

100 queries:

```
SELECT *
FROM V
WHERE P=?
```

A: V(N) and V(P) (hash tables or B-trees)

Index Selection Problem 2

```
V(M, N, P)
```

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N>? and N<?
```

100 queries:

```
SELECT *
FROM V
WHERE P=?
```

100000 queries:

```
INSERT INTO V
VALUES (?, ?, ?)
```

Which indexes should we create?

Index Selection Problem 2

V(M, N, P)

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N>? and N<?
```

100 queries:

```
SELECT *
FROM V
WHERE P=?
```

100000 queries:

```
INSERT INTO V
VALUES (?, ?, ?)
```

A: definitely V(N) (must B-tree); unsure about V(P)

Index Selection Problem 3

V(M, N, P)

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N=?
```

1000000 queries:

```
SELECT *
FROM V
WHERE N=? and P>?
```

100000 queries:

```
INSERT INTO V
VALUES (?, ?, ?)
```

Which indexes should we create?

Index Selection Problem 3

V(M, N, P)

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N=?
```

1000000 queries:

```
SELECT *
FROM V
WHERE N=? and P>?
```

100000 queries:

```
INSERT INTO V
VALUES (?, ?, ?)
```

A: V(N, P) (must be B-tree)

Index Selection Problem 4

V(M, N, P)

Your workload is this

1000 queries:

```
SELECT *
FROM V
WHERE N>? and N<?
```

100000 queries:

```
SELECT *
FROM V
WHERE P>? and P<?
```

Which indexes should we create?

Index Selection Problem 4

V(M, N, P)

Your workload is this

1000 queries:

```
SELECT *
FROM V
WHERE N>? and N<?
```

100000 queries:

```
SELECT *
FROM V
WHERE P>? and P<?
```

A: V(N) secondary, V(P) primary index