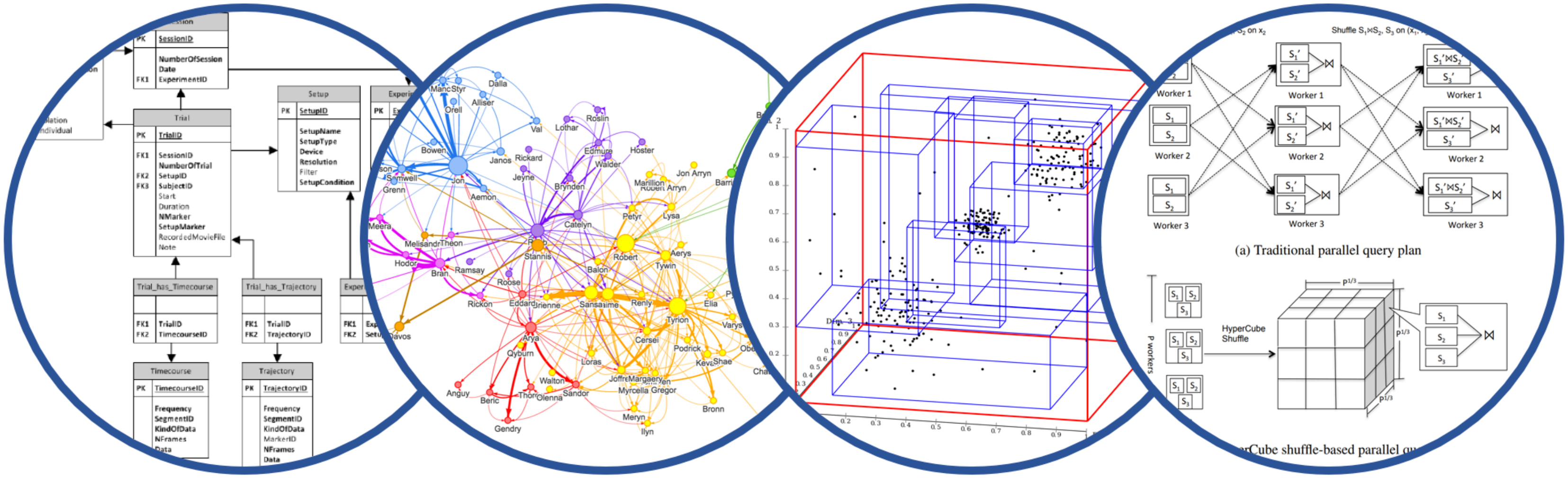

# Database System Internals

# Indexing

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# Announcements

- Homework 1:
  - Due on gradescope 11pm tonight

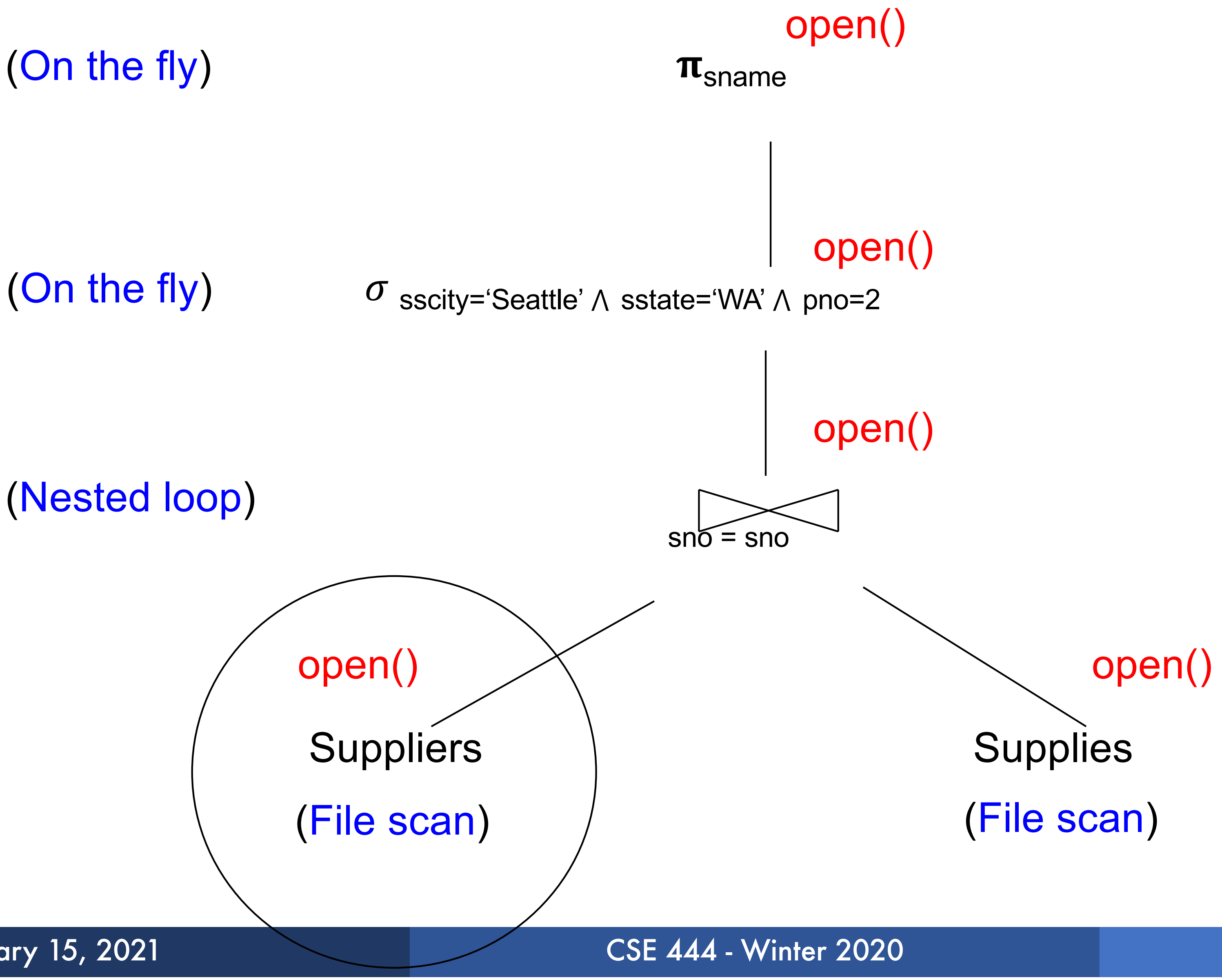
- Lab 1 complete:
  - Due on Jan. 20th

- 544 reading 1:
  - Due approx. this weekend (these due dates are flexible) by email to me

# Heap File Access Method 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 (more next lecture)
- **Scan** all records in the file

# Query Execution   How it all Fits



(On the fly) $\pi_{\text{sname}}$ open()

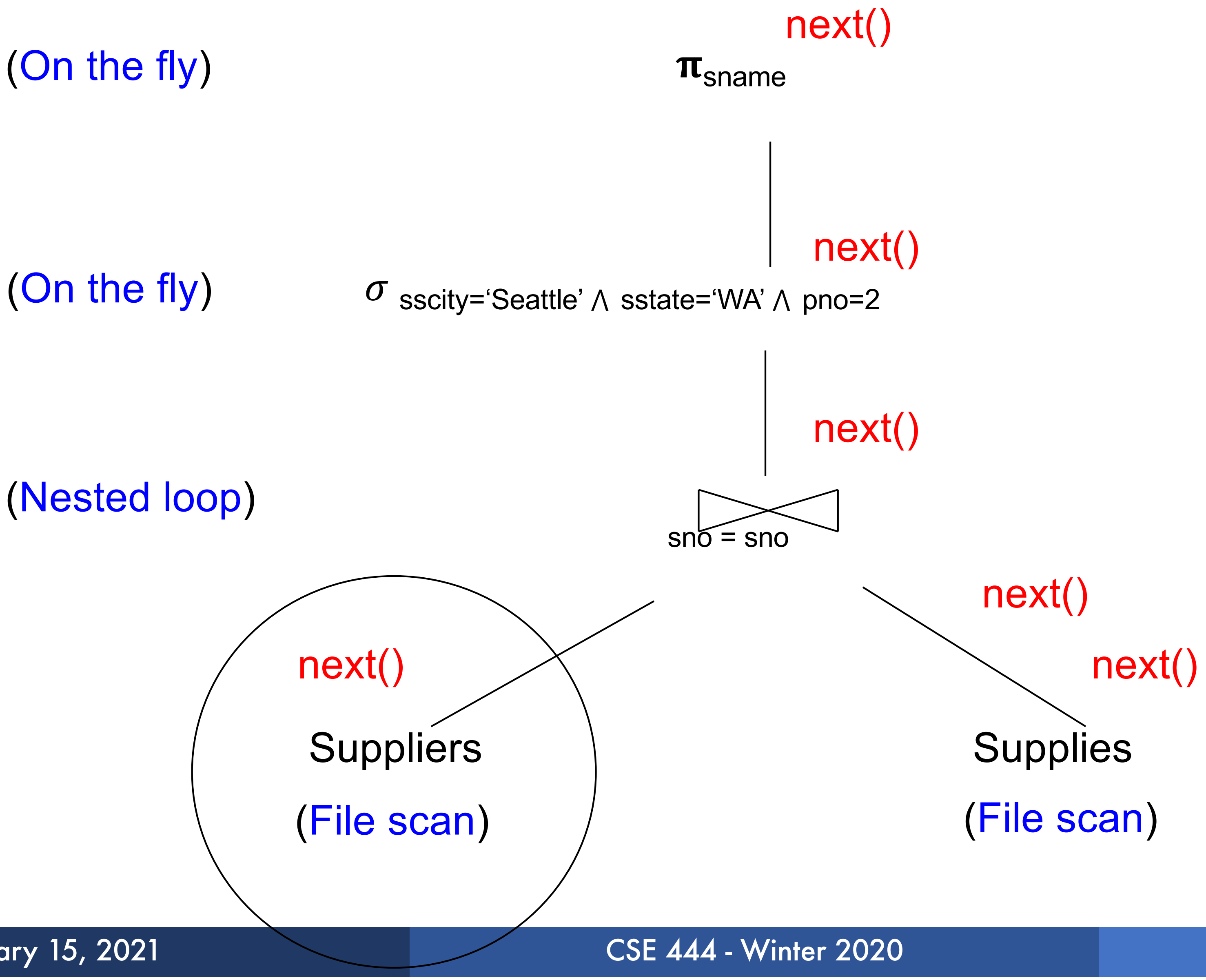
(On the fly) $\sigma_{\text{sscity='Seattle'} \wedge \text{sstate='WA'} \wedge \text{pno=2}}$ open()

(Nested loop) $\bowtie_{\text{sno = sno}}$ open()

open() Suppliers (File scan)

open() Supplies (File scan)

# Query Execution How it all Fits



next()

(On the fly) $\pi_{sname}$

next()

(On the fly) $\sigma_{sscity='Seattle' \wedge sstate='WA' \wedge pno=2}$

next()

(Nested loop) $\bowtie_{sno = sno}$

next()

next()

next()

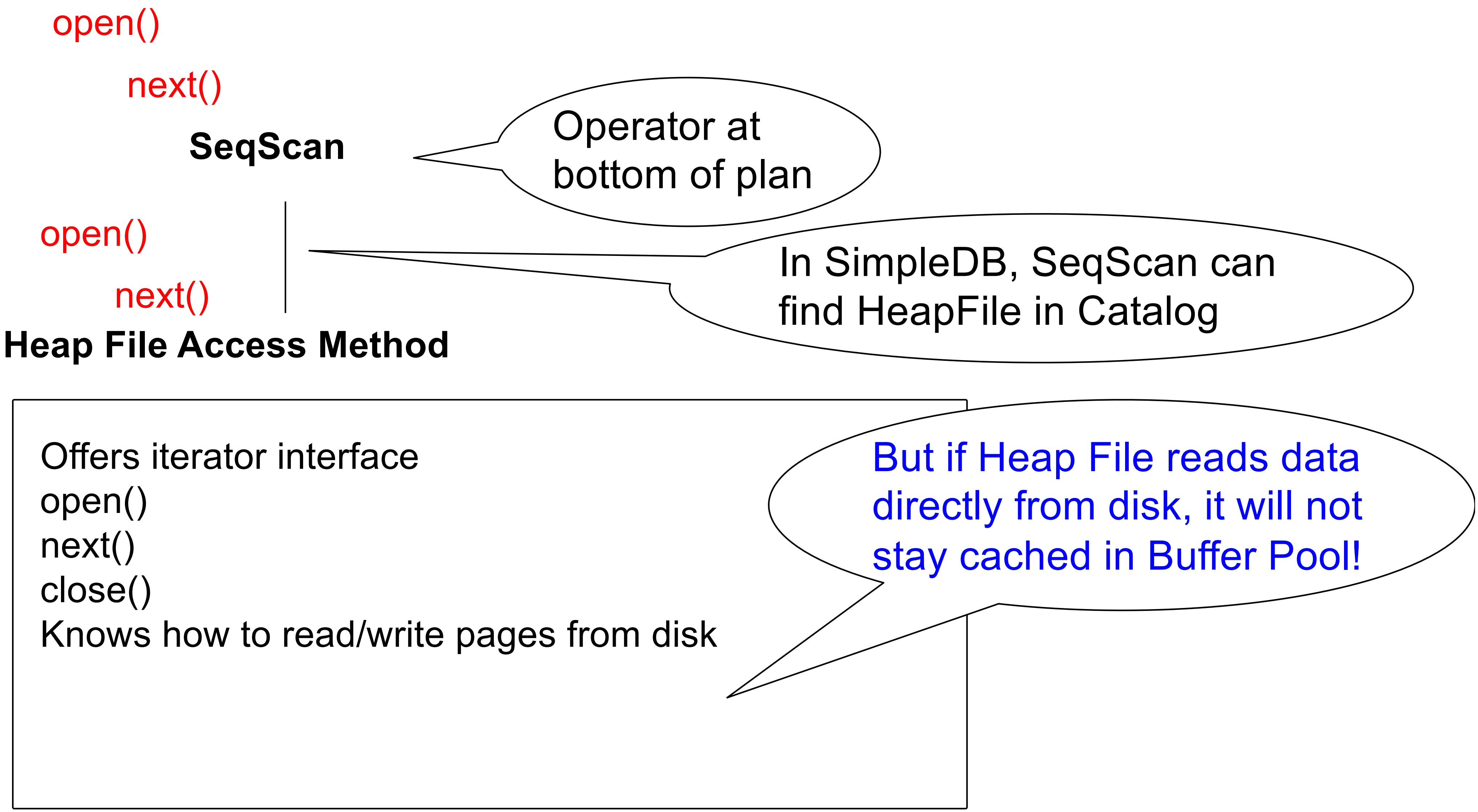
Suppliers

(File scan)

Supplies

(File scan)

# Query Execution In SimpleDB



open()

next()

**SeqScan**

Operator at bottom of plan

open()

next()

**Heap File Access Method**

In SimpleDB, SeqScan can find HeapFile in Catalog

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!

# Iterators in SimpleDB

- SeqScan.java

- DbFileIterator.java

- Both have this method:
  public Tuple next()

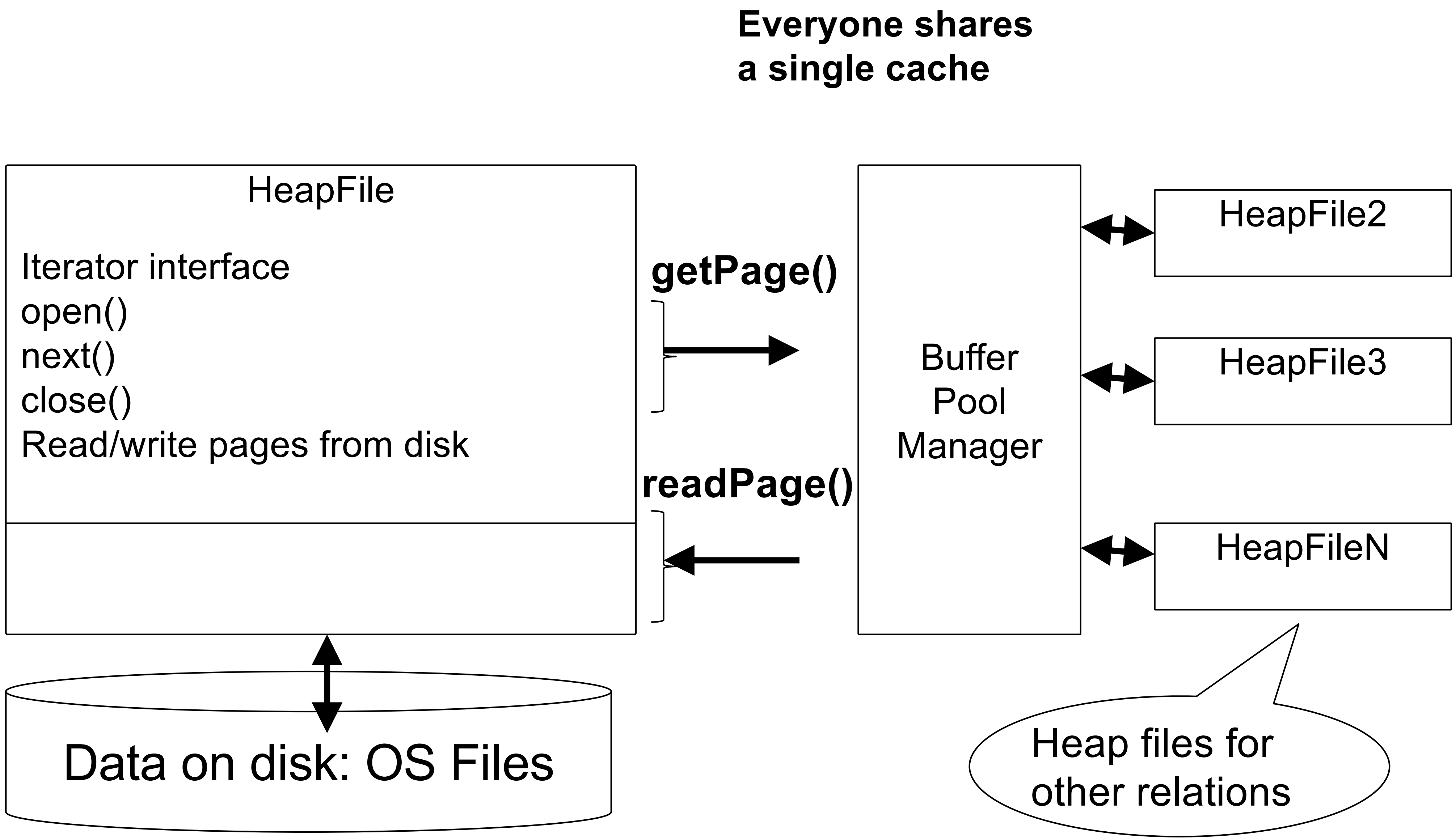
# Iterators in SimpleDB

- How does DbFileIterator.java get its tuples?

- Needs pages from buffer pool

- Buffer pool has this method:
  **getPage()**

# Query Execution In SimpleDB



**Everyone shares a single cache**

HeapFile

Iterator interface
open()
next()
close()
Read/write pages from disk

**getPage()**

**readPage()**

Buffer Pool Manager

HeapFile2

HeapFile3

HeapFileN

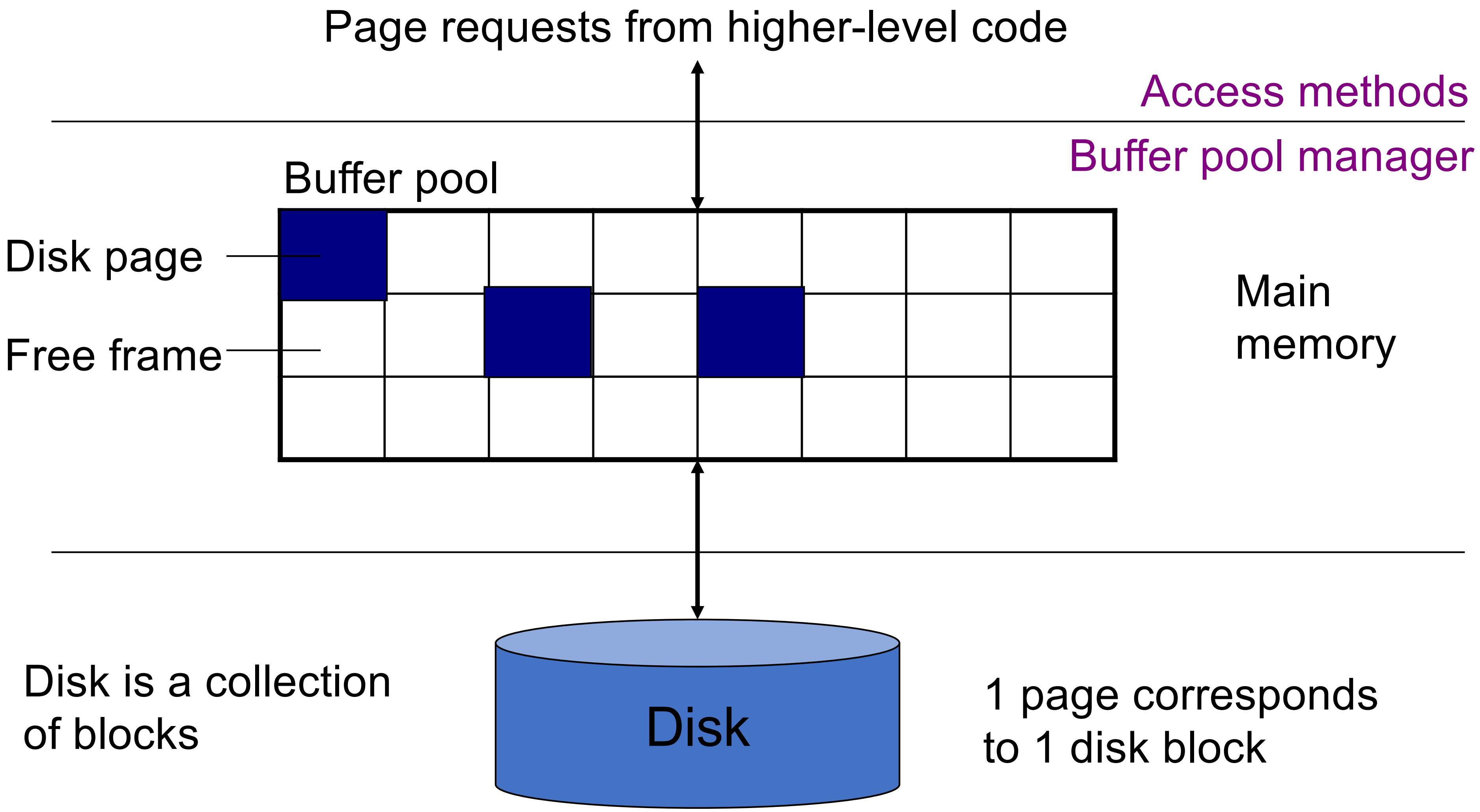
Data on disk: OS Files

Heap files for other relations

# Buffer Manager

- Brings pages in from memory and caches them
- Eviction policies
  - Random page (ok for SimpleDB)
  - Least-recently used
  - The "clock" algorithm
- Keeps track of which **pages are dirty**
  - A dirty page has changes not reflected on disk
  - Implementation: Each page includes a dirty bit

# Buffer Manager



Page requests from higher-level code

Access methods

Buffer pool manager

Buffer pool

Disk page

Free frame

Main memory

Disk

Disk is a collection of blocks

1 page corresponds to 1 disk block

# 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

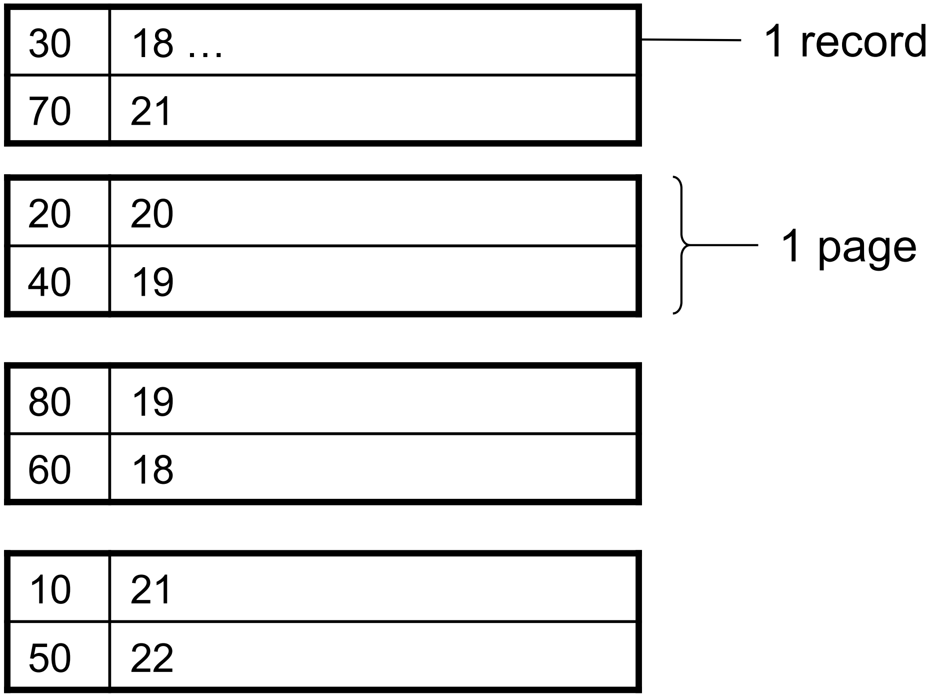
- Critical to support such requests efficiently
  - Why read all data form disk when we only need a small fraction of that data?

- 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, …)`



|    |        |
|----|--------|
| 30 | 18 … |
| 70 | 21 |

|    |    |
|----|----|
| 20 | 20 |
| 40 | 19 |

|    |    |
|----|----|
| 80 | 19 |
| 60 | 18 |

|    |    |
|----|----|
| 10 | 21 |
| 50 | 22 |

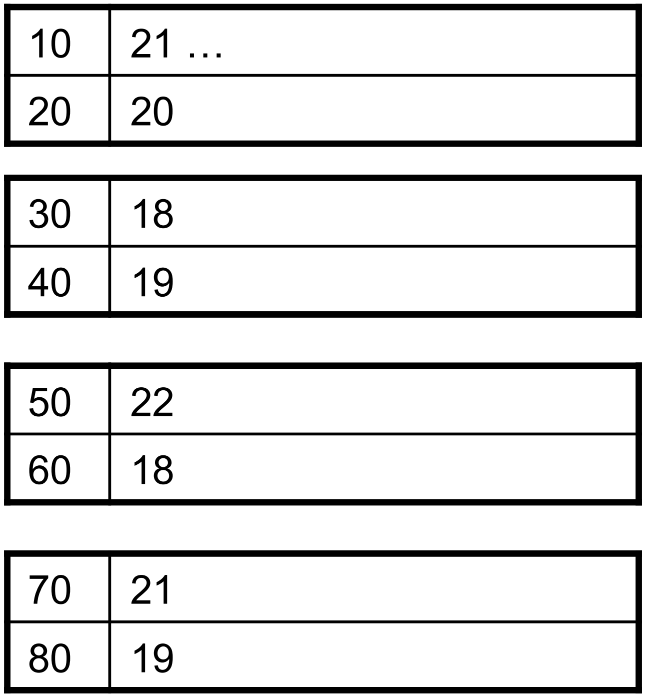
# Heap File Search Example

- 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?

- Note: Sorted files are inefficient for inserts/deletes

# Creating Indexes in SQL

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

```
CREATE  INDEX V1 ON V(N)
```

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

```
select  *
from V
where P=55 and M=77
```

```
select  *
from V
where P=55
```

# Outline

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

Today

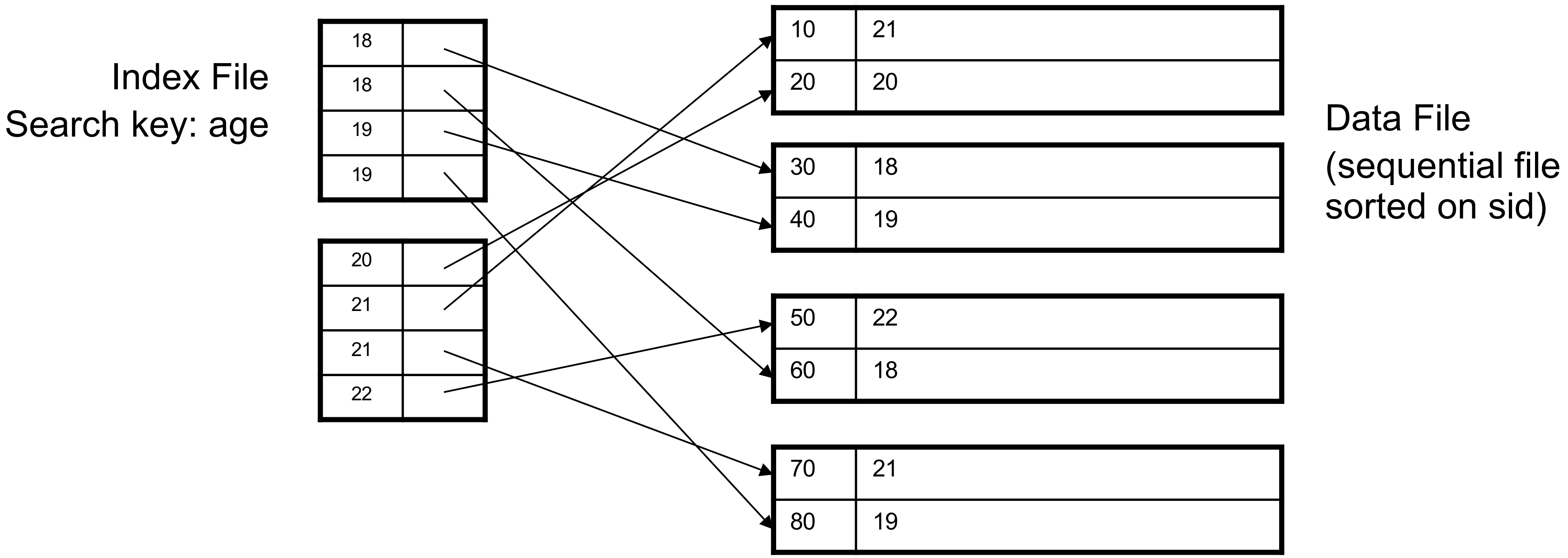
Next time

# 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 predicate on search key



Index File
Search key: age

| | |
|---|---|
| 18 | |
| 18 | |
| 19 | |
| 19 | |

| | |
|---|---|
| 20 | |
| 21 | |
| 21 | |
| 22 | |

| | |
|---|---|
| 10 | 21 |
| 20 | 20 |

| | |
|---|---|
| 30 | 18 |
| 40 | 19 |

| | |
|---|---|
| 50 | 22 |
| 60 | 18 |

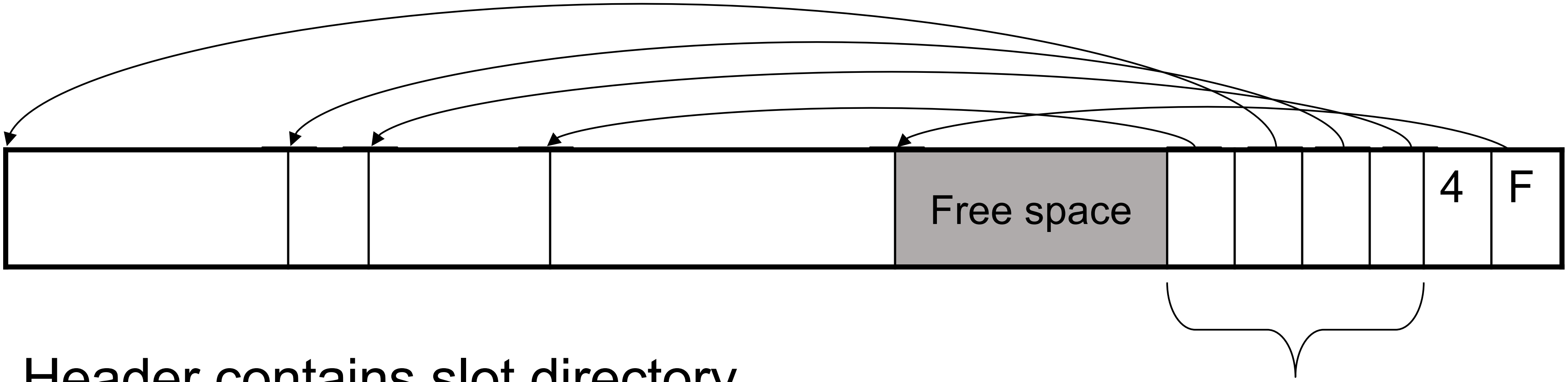
| | |
|---|---|
| 70 | 21 |
| 80 | 19 |

Data File
(sequential file sorted on sid)

# 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:
  - (k, RID)
  - (k, list-of-RIDs)
  - The actual record with key k
    - In this case, **the index is also a special file organization**
    - Called: "indexed file organization"

# Page Format Approach 2



Slot directory

Each slot contains
<record offset, record length>

Header contains slot directory

+ Need to keep track of # of slots

+ Also need to keep track of free space (F)

Can handle variable-length records

Can move tuples inside a page without changing RIDs

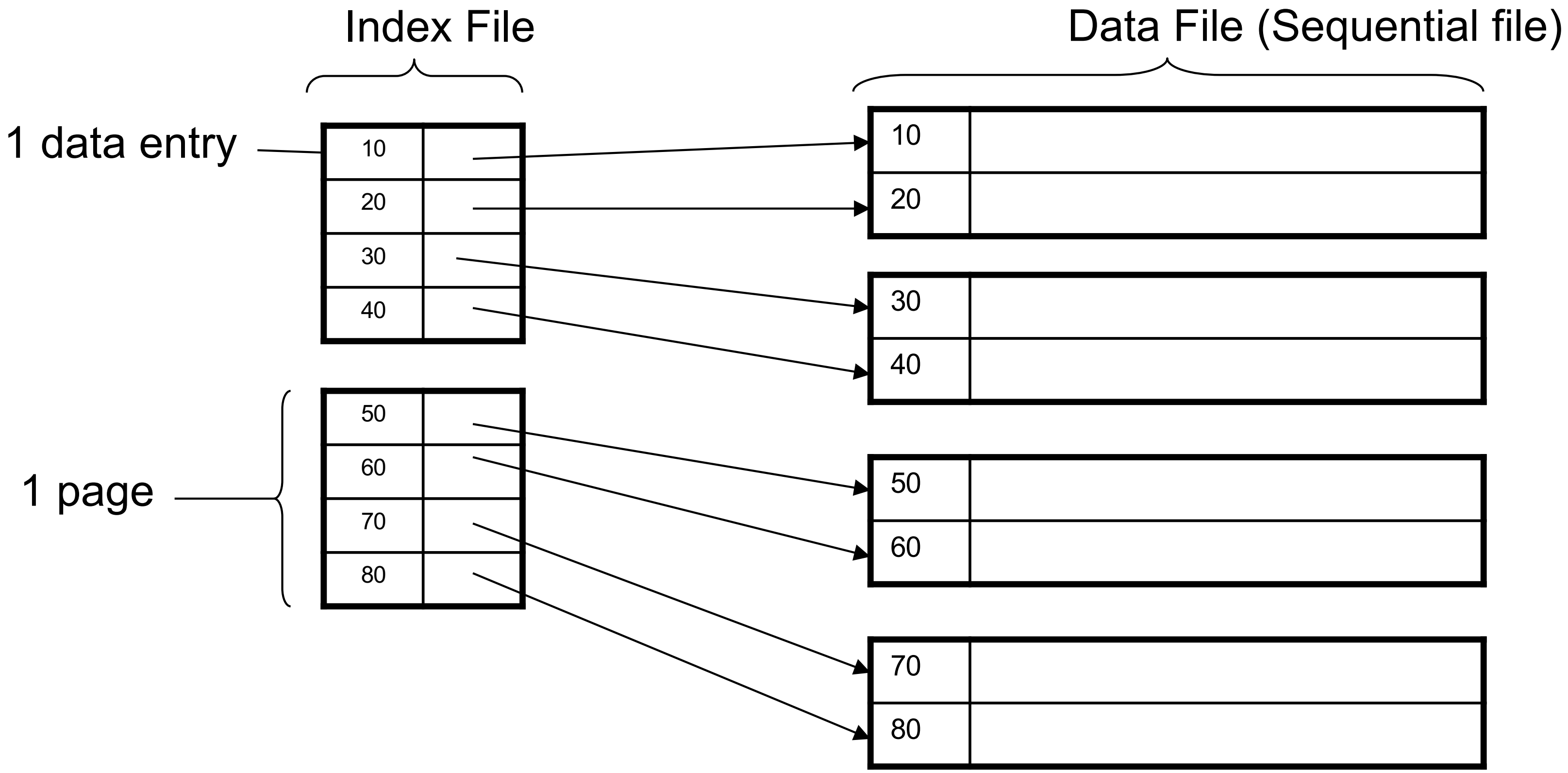
RID is (PageID, SlotID) combination

# Different Types of Files

- For the data inside base relations:
  - Heap file (tuples stored without any order)
  - Sequential file (tuples sorted on 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

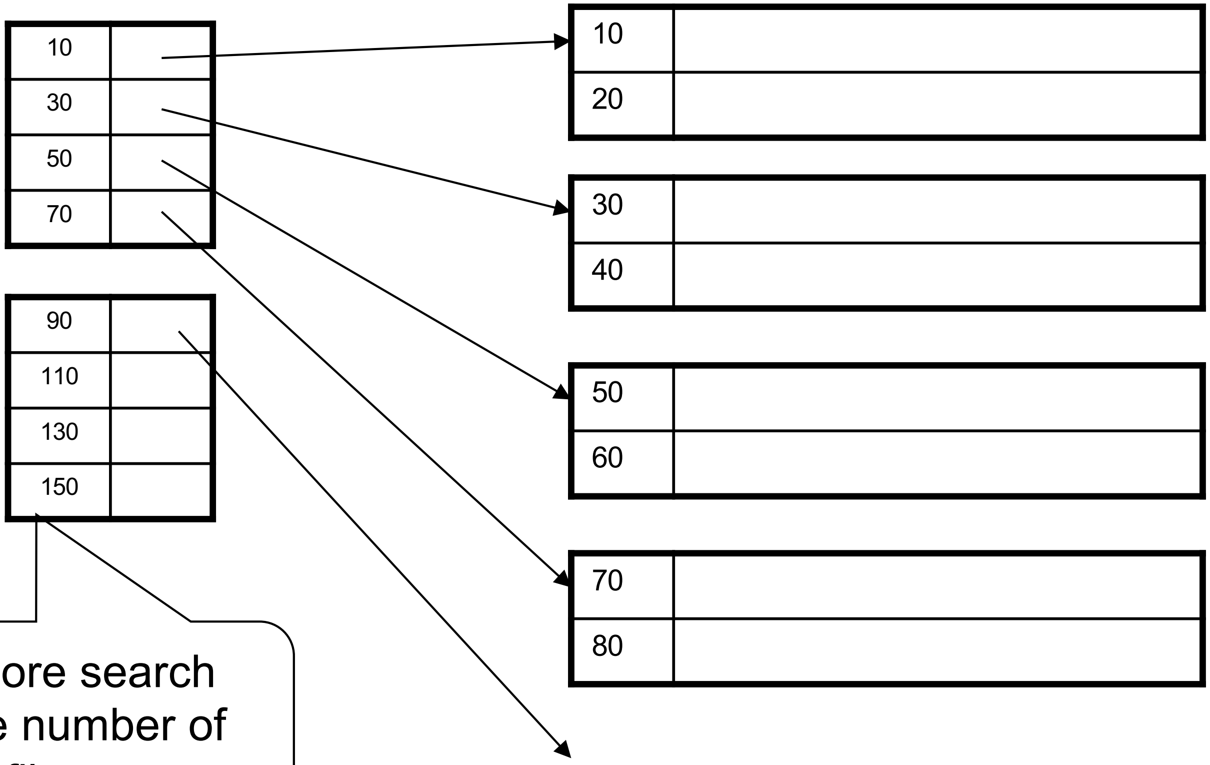
# Primary Index

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



# Primary Index

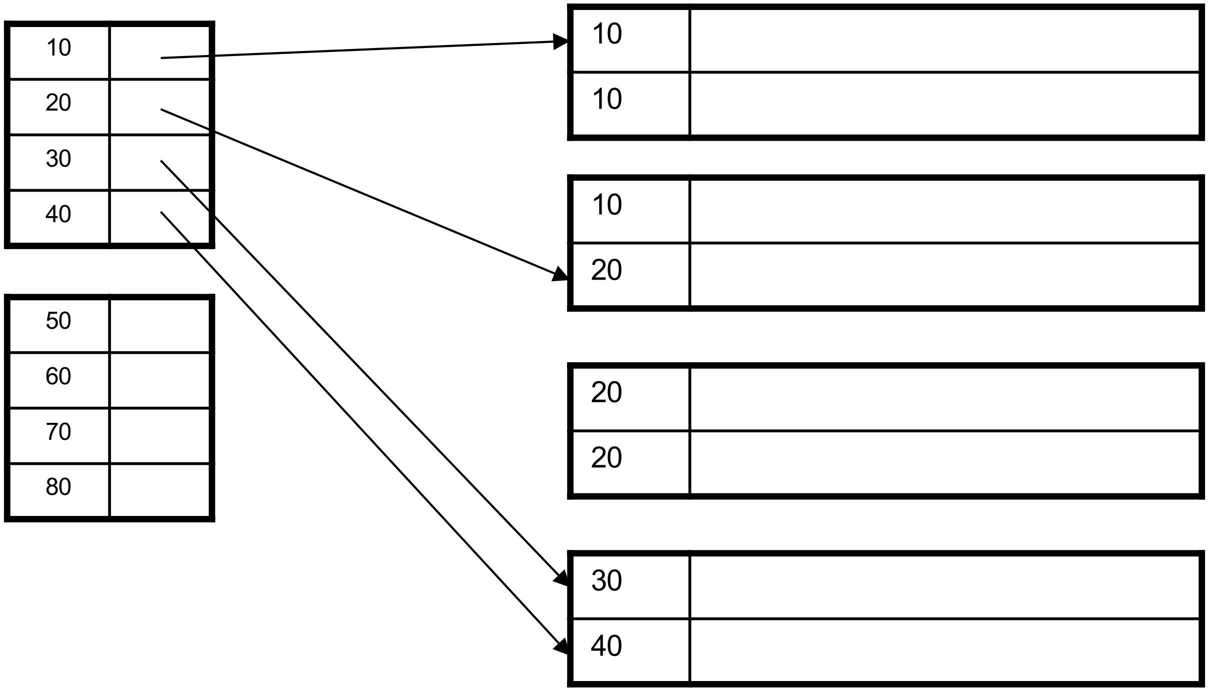
- Sparse index



Can store more search keys in same number of index files

# Primary Index with Duplicate Keys

- Dense index:



# Primary Index: Back to Example

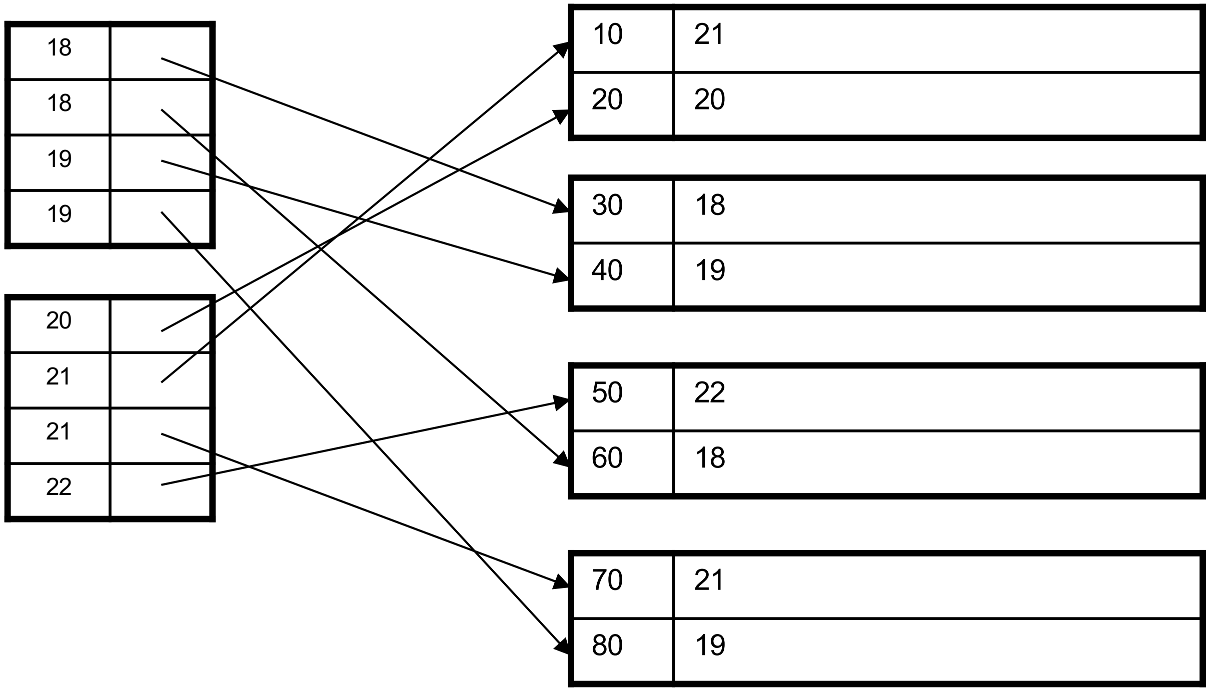
- Let’s assume all pages of index fit in memory

- 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

- How can we make *both* queries fast?

# Secondary Indexes

- Do not determine placement of records in data files
- Always dense (why ?)



18
18
19
19

20
21
21
22

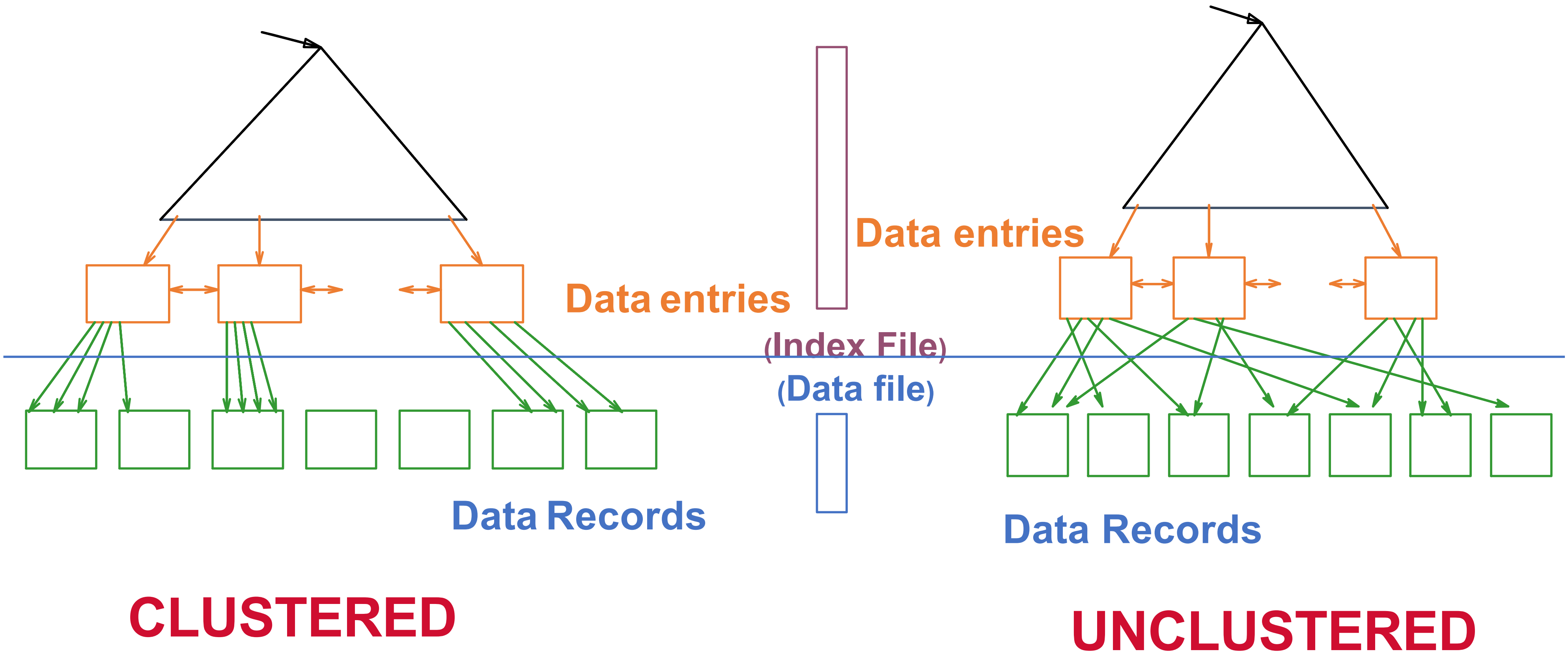
10 21
20 20

30 18
40 19

50 22
60 18

70 21
80 19

# 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 unsorted files (heap files)
  - When necessary to have multiple indexes
  - Index files that hold data from two relations

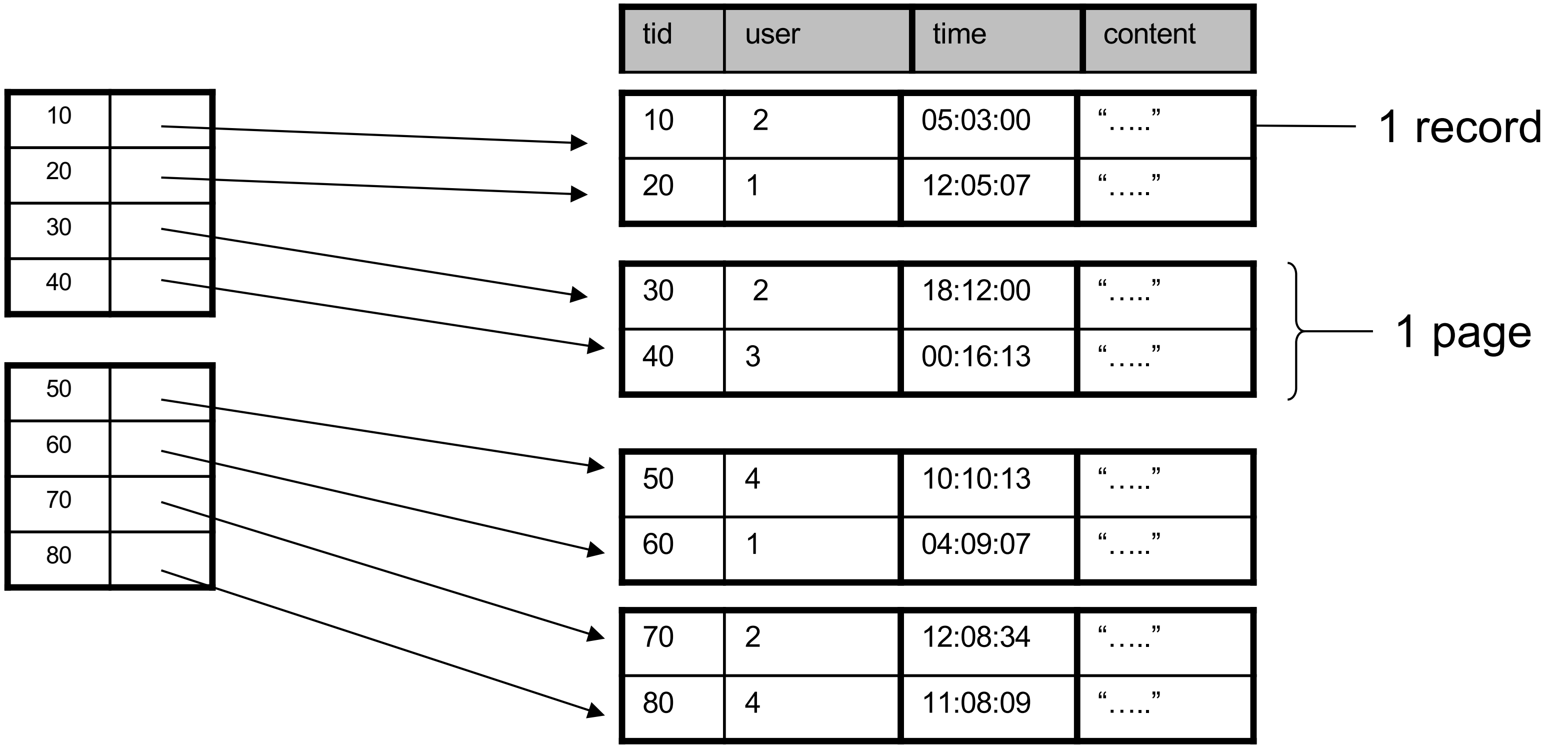
# Index Classification Summary

- 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 / …

# Ex1. Primary Dense Index (tid)



| | |
|---|---|
| 10 | |
| 20 | |
| 30 | |
| 40 | |

| | |
|---|---|
| 50 | |
| 60 | |
| 70 | |
| 80 | |

| tid | user | time | content |
|---|---|---|---|
| 10 | 2 | 05:03:00 | “…..” |
| 20 | 1 | 12:05:07 | “…..” |
| 30 | 2 | 18:12:00 | “…..” |
| 40 | 3 | 00:16:13 | “…..” |
| 50 | 4 | 10:10:13 | “…..” |
| 60 | 1 | 04:09:07 | “…..” |
| 70 | 2 | 12:08:34 | “…..” |
| 80 | 4 | 11:08:09 | “…..” |

- **Dense:** an “index key” for every database record
  - (In this case) every “database key” appears as an “index key”
- **Primary:** determines the location of indexed records
- Also, **Clustered:** records close in index are close in data

Improve from Primary Clustered Index?

Clustered Index can be made Sparse
(normally one key per page)

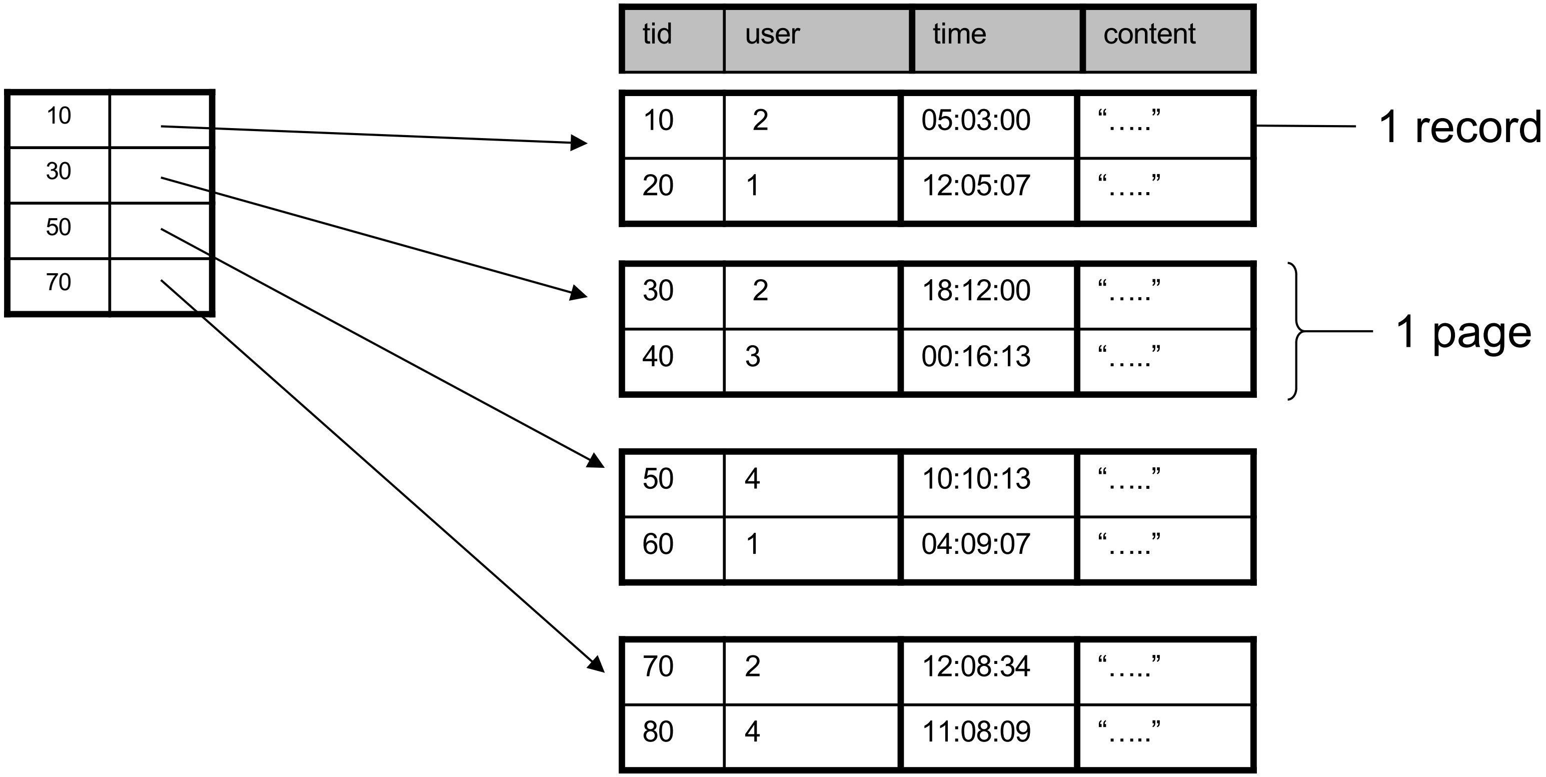
# Ex2. Draw a <u>primary</u> <u>sparse</u> index on “tid”

| tid | user | time | content |
|---|---|---|---|
| 10 | 2 | 05:03:00 | “…..” |
| 20 | 1 | 12:05:07 | “…..” |
| 30 | 2 | 18:12:00 | “…..” |
| 40 | 3 | 00:16:13 | “…..” |
| 50 | 4 | 10:10:13 | “…..” |
| 60 | 1 | 04:09:07 | “…..” |
| 70 | 2 | 12:08:34 | “…..” |
| 80 | 4 | 11:08:09 | “…..” |

1 record

1 page

# Ex2. Primary Sparse Index (tid)



| | |
|---|---|
| 10 | |
| 30 | |
| 50 | |
| 70 | |

| tid | user | time | content |
|---|---|---|---|
| 10 | 2 | 05:03:00 | "….." |
| 20 | 1 | 12:05:07 | "….." |
| 30 | 2 | 18:12:00 | "….." |
| 40 | 3 | 00:16:13 | "….." |
| 50 | 4 | 10:10:13 | "….." |
| 60 | 1 | 04:09:07 | "….." |
| 70 | 2 | 12:08:34 | "….." |
| 80 | 4 | 11:08:09 | "….." |

- Only one index file page instead of two

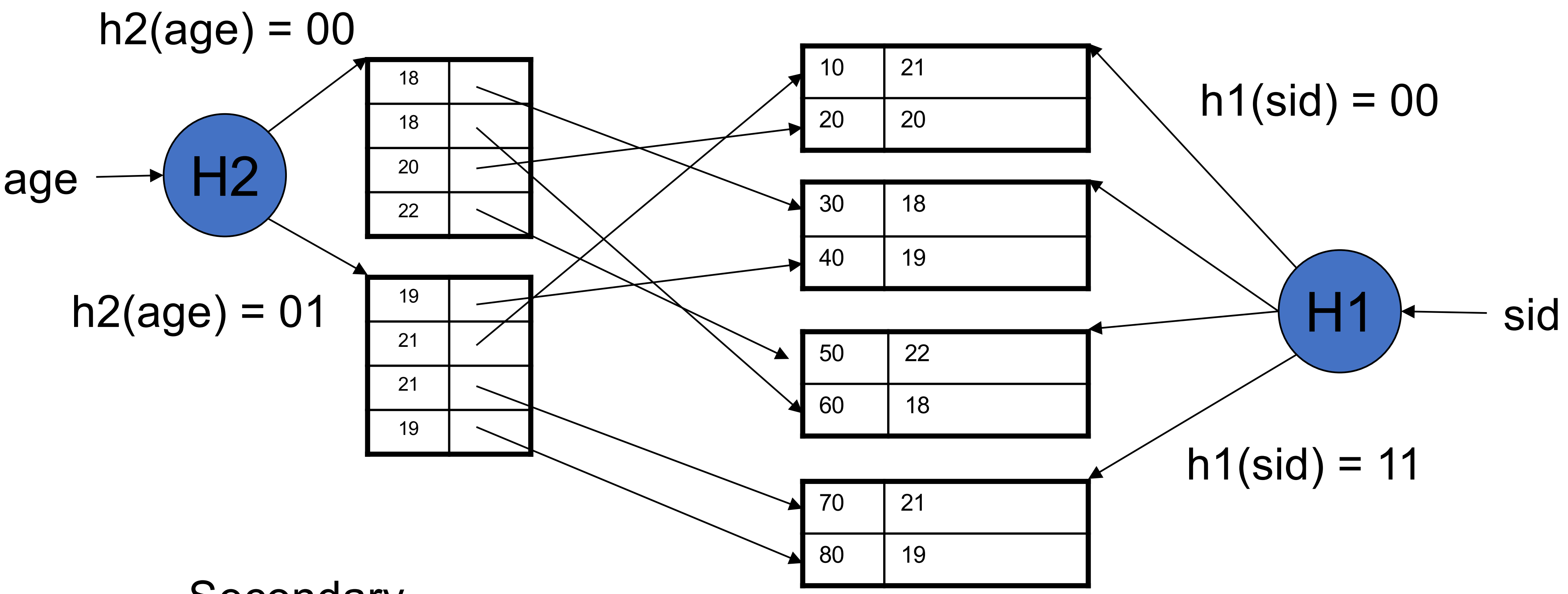
# Large Indexes

- 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



| | |
|---|---|
| 18 | |
| 18 | |
| 20 | |
| 22 | |

| | |
|---|---|
| 19 | |
| 21 | |
| 21 | |
| 19 | |

| | |
|---|---|
| 10 | 21 |
| 20 | 20 |

| | |
|---|---|
| 30 | 18 |
| 40 | 19 |

| | |
|---|---|
| 50 | 22 |
| 60 | 18 |

| | |
|---|---|
| 70 | 21 |
| 80 | 19 |

Secondary
hash-based index
(age, rid) pairs

Primary hash-based index

# Tree-Based Index

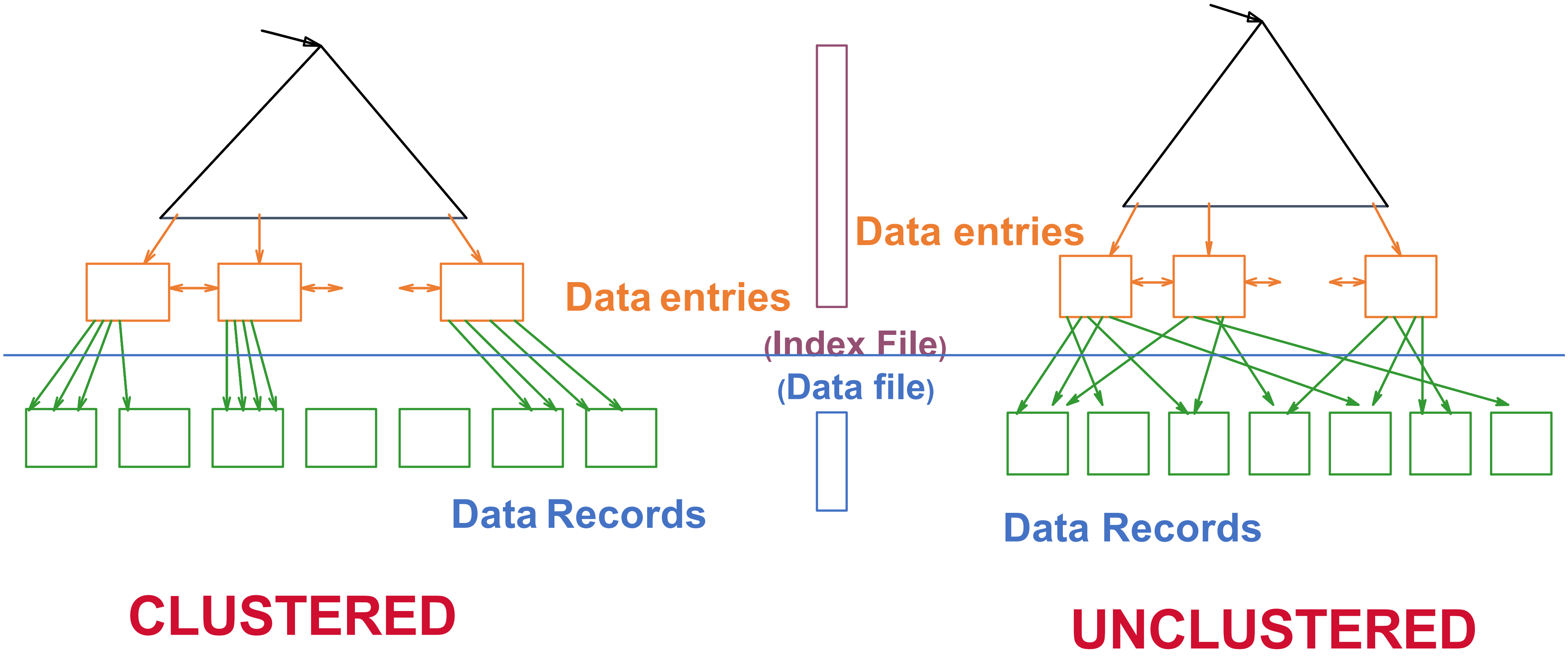
- How many index levels do we need?
- Can we create them automatically? Yes!
- Can do something even more powerful!

# B+ Trees

- Search trees

- Idea in B Trees
  - Make 1 node = 1 page (= 1 block)

- Idea in B+ Trees
  - Keep tree balanced in height – dynamic rather than static
  - Make leaves into a linked list : facilitates range queries



Data entries

(Index File)

(Data file)

Data entries

Data Records

Data Records

CLUSTERED

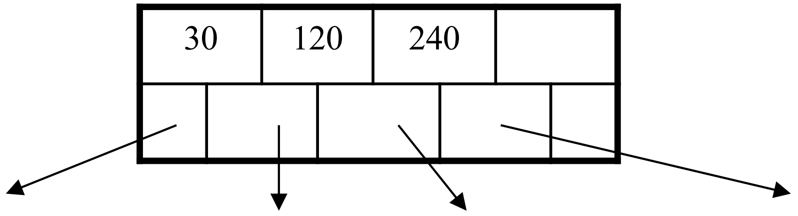
UNCLUSTERED

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**

Left pointer of k:
to keys < k



30 120 240

Right pointer of k:
to keys >= k

Keys k < 30

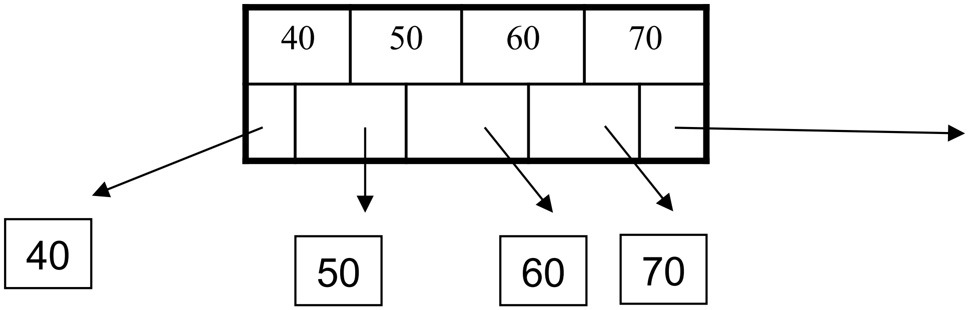
Keys 30<=k<120

Keys 120<=k<240

Keys 240<=k

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

Data records



40 50 60 70

40

50

60

70

Next leaf

# B+ Trees Properties

- For each node except the root, maintain 50% occupancy of keys
- Insert and delete must rebalance to maintain constraints

# 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

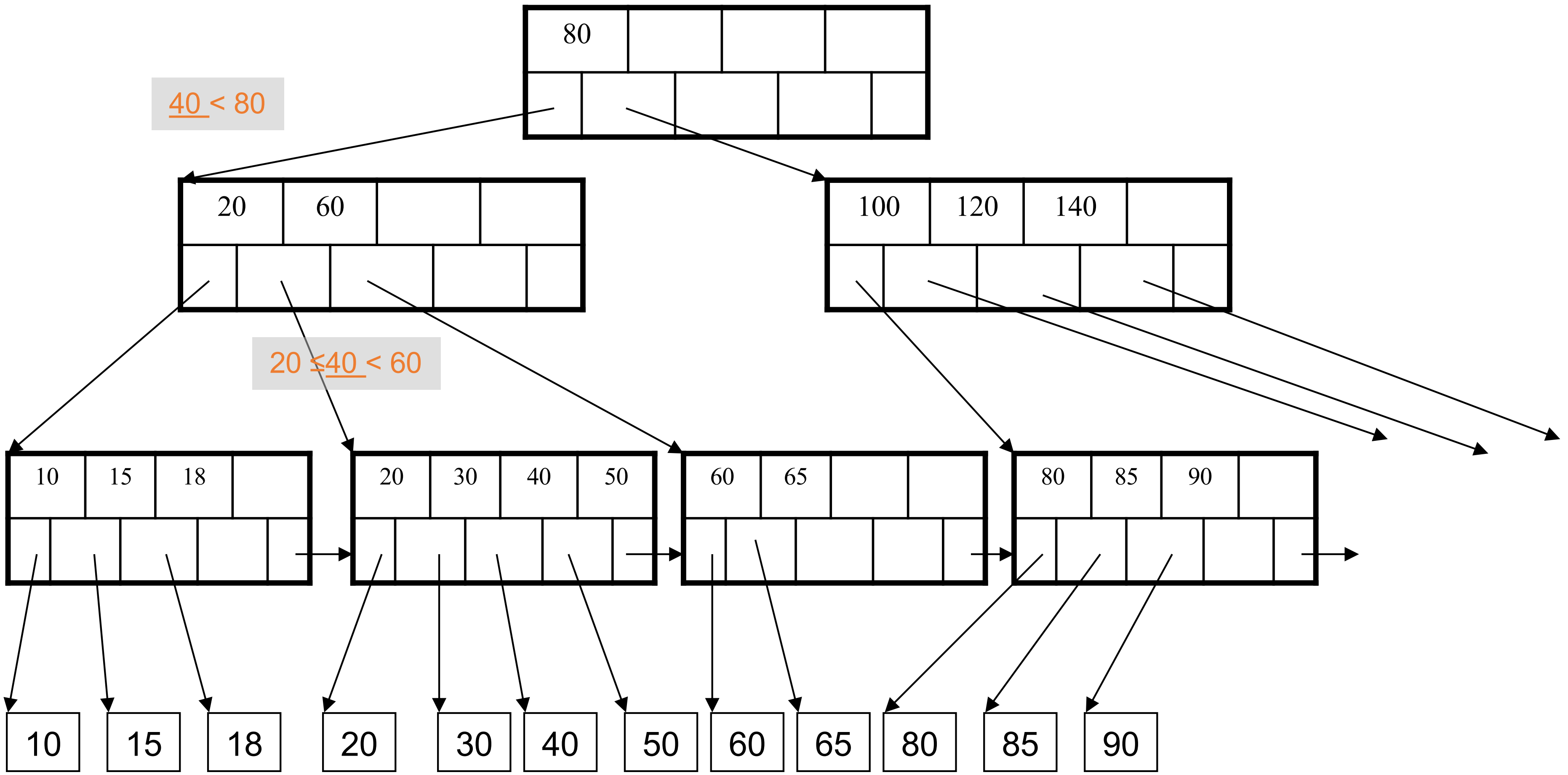
```
Select name
From Student
Where age = 25
```

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

# B+ Tree Example

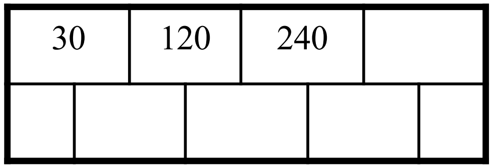
d = 2

Find the key 40



# B+ Tree Design

- How large d ? Make one node fit on one block
- Example:
  - Key size = 4 bytes
  - Pointer size = 8 bytes
  - Block size = 4096 bytes



(e.g. d = 2)

- $2d \times 4 + (2d+1) \times 8 \leq 4096$
- $d = 170$

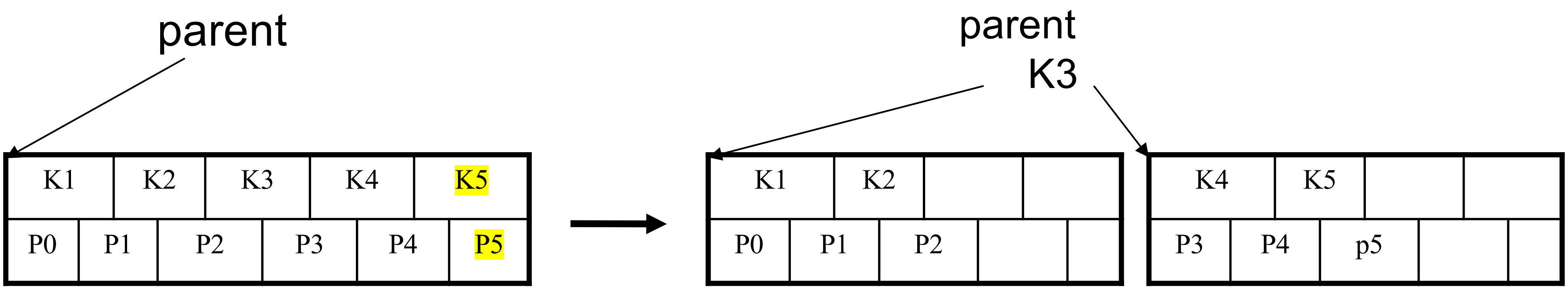
# B+ Trees in Practice

- 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)

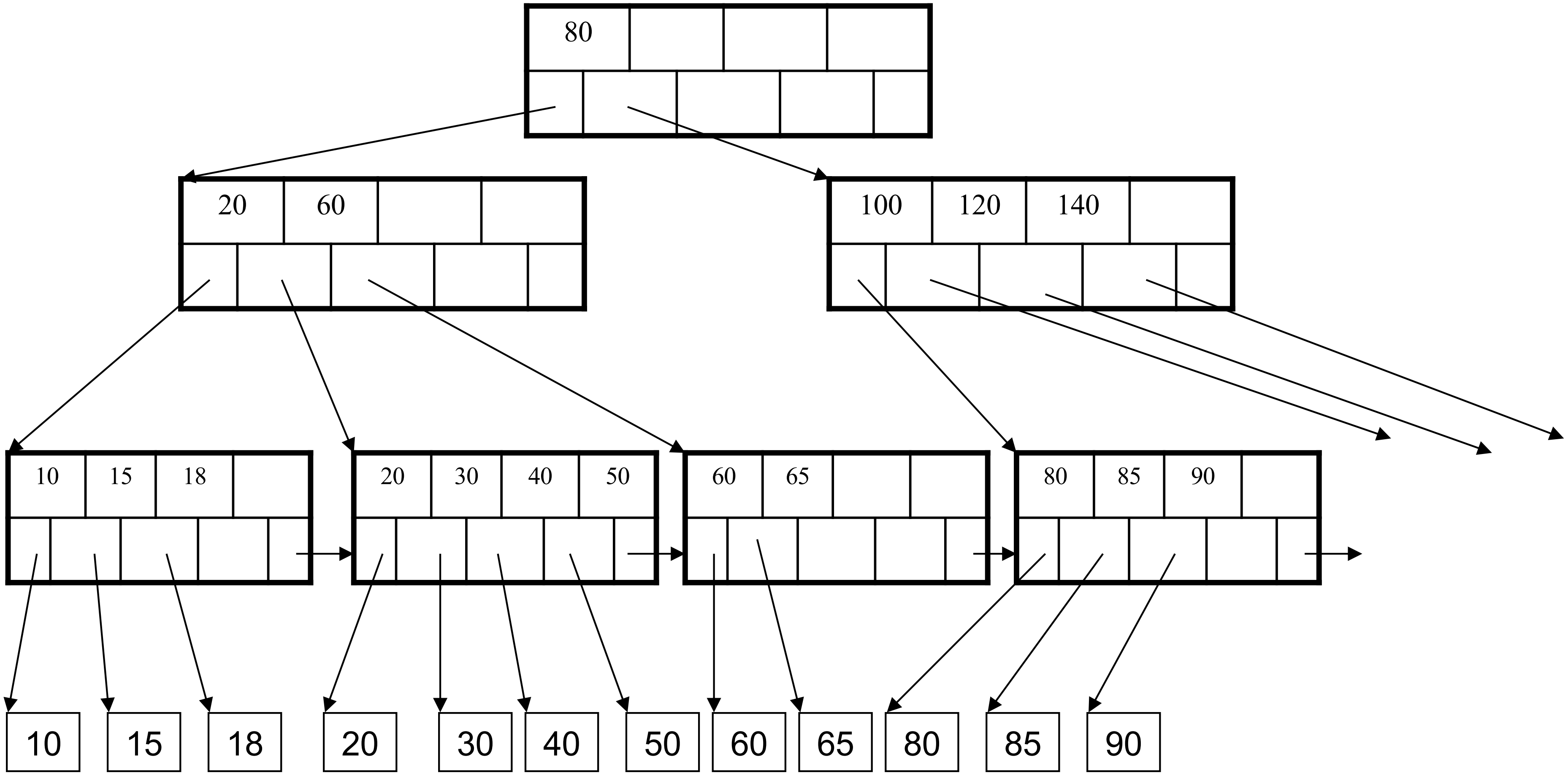
- Find leaf where K belongs, insert
- If no overflow (2d keys or less), halt
- If overflow (2d+1 keys), split node, insert in parent:



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

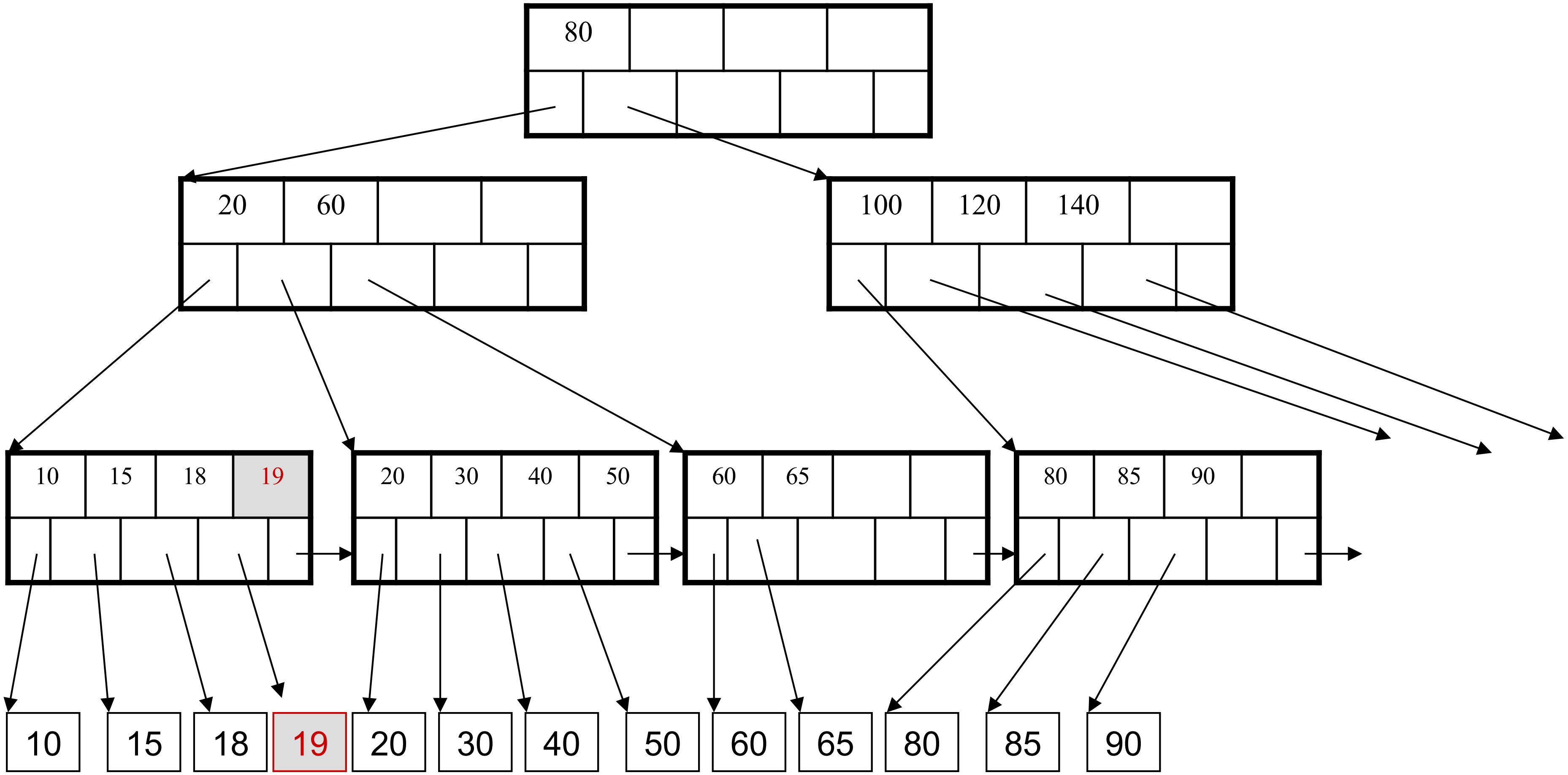
# Insertion in a B+ Tree

Insert K=19



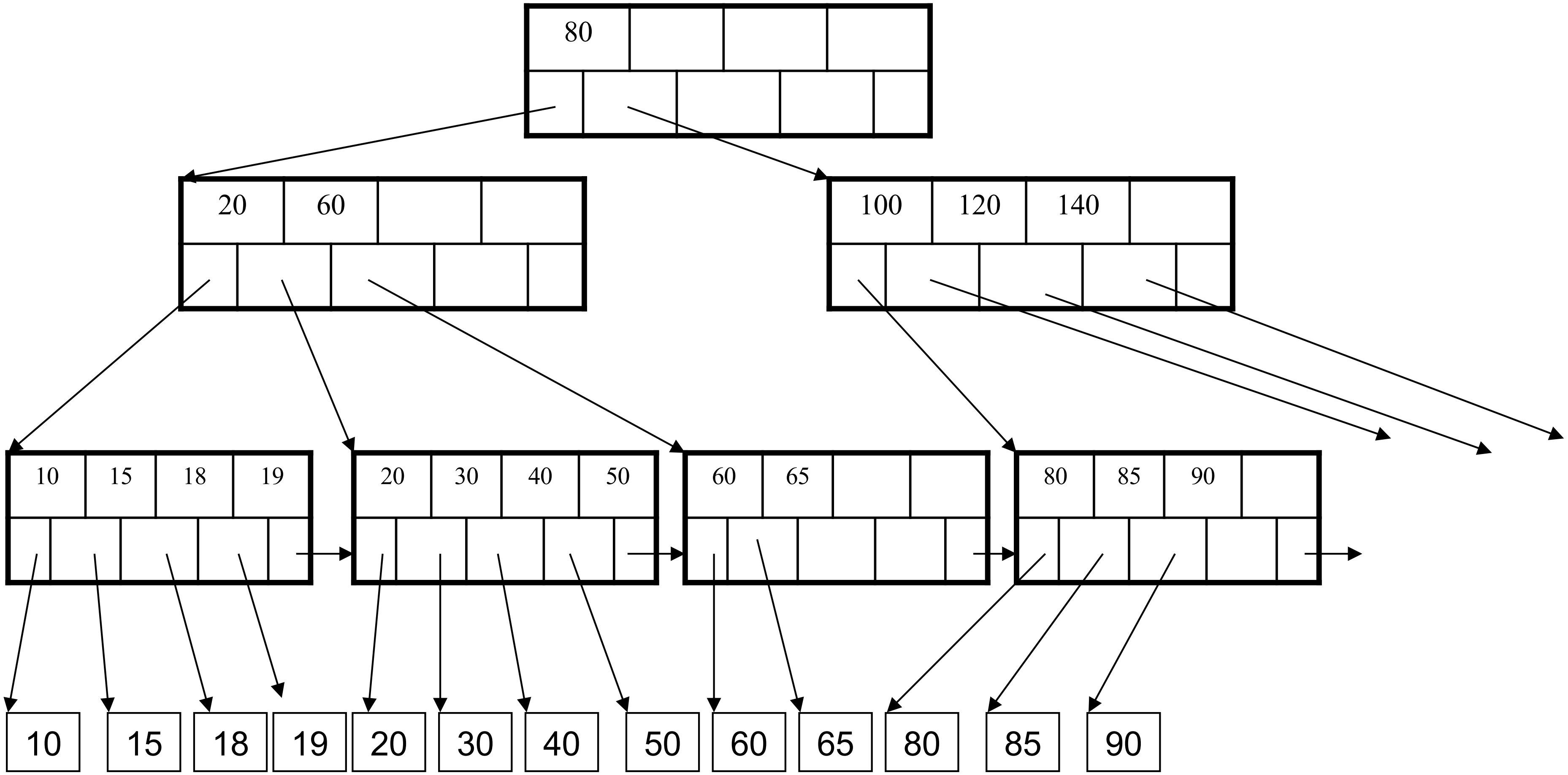
# Insertion in a B+ Tree

After insertion



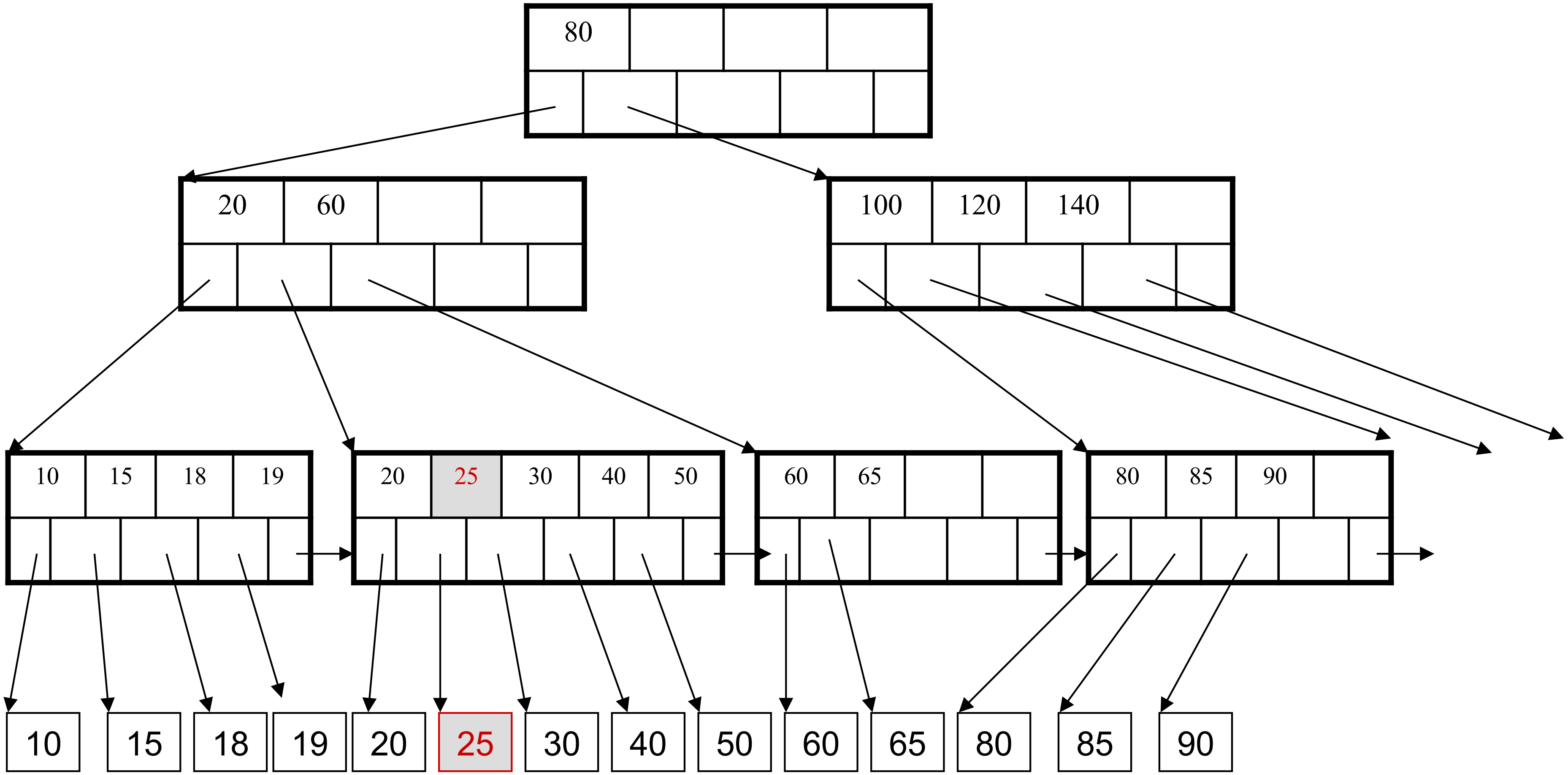
# Insertion in a B+ Tree

Now insert 25



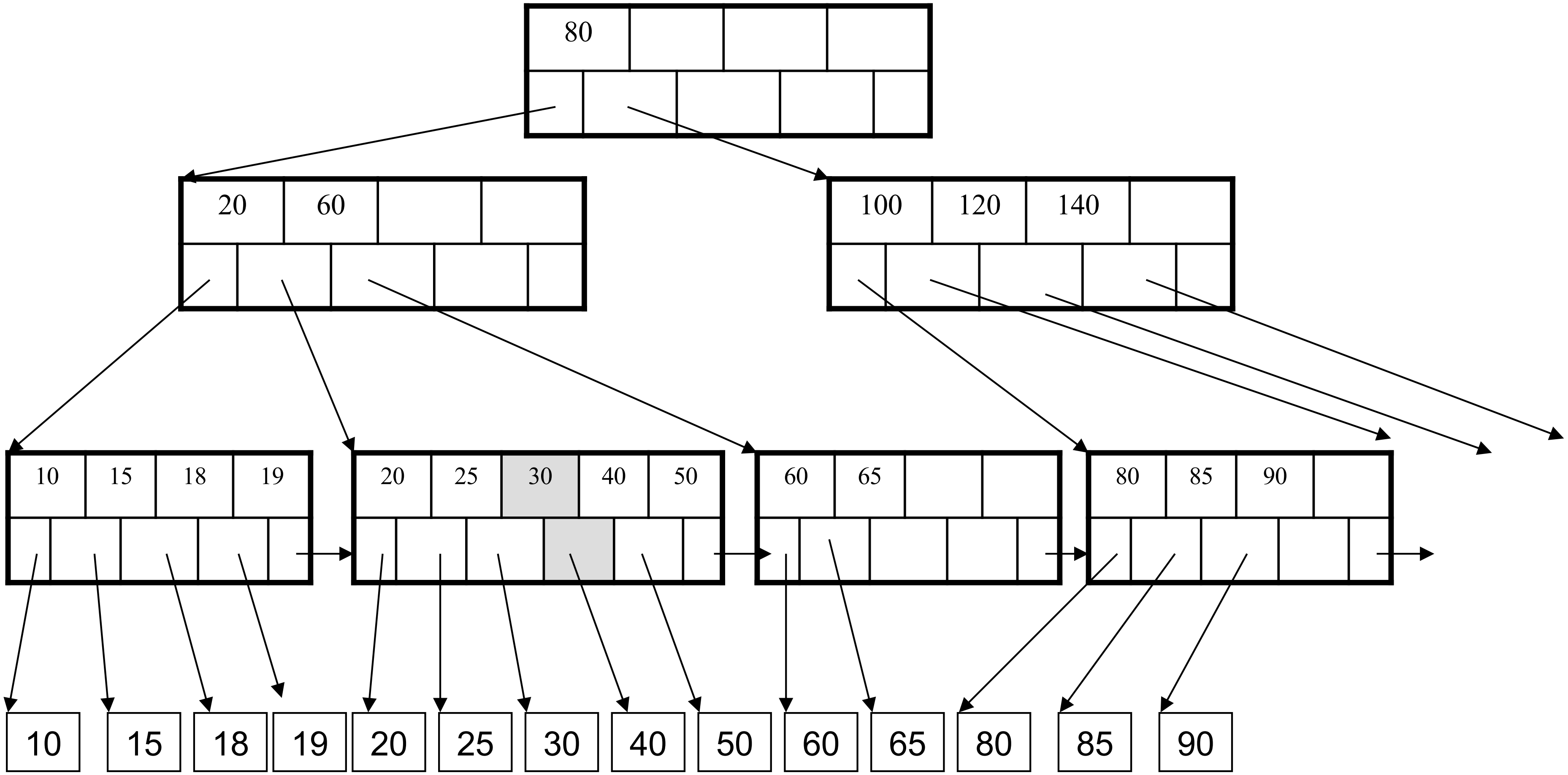
# Insertion in a B+ Tree

After insertion



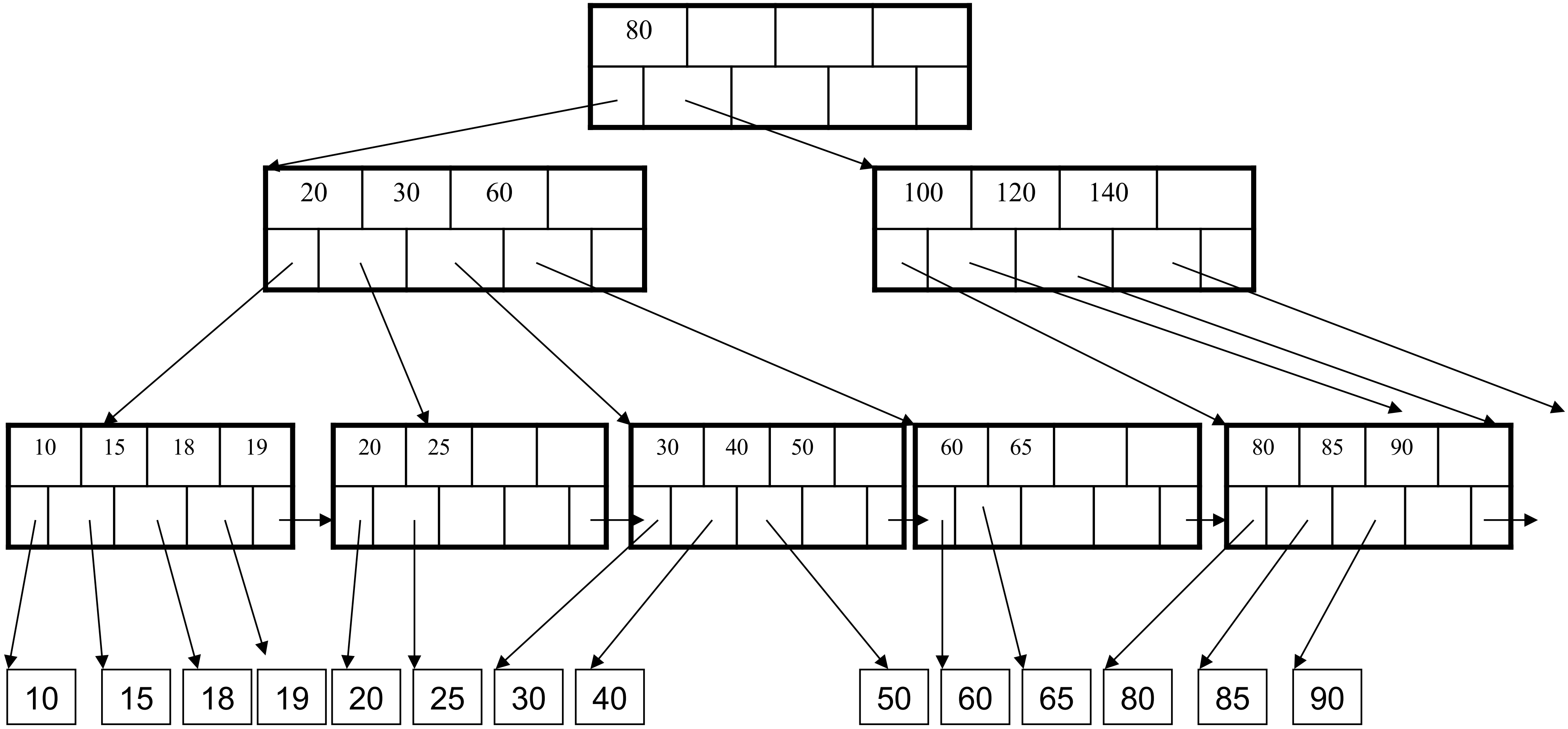
# Insertion in a B+ Tree

But now have to split !



# Insertion in a B+ Tree

After the split



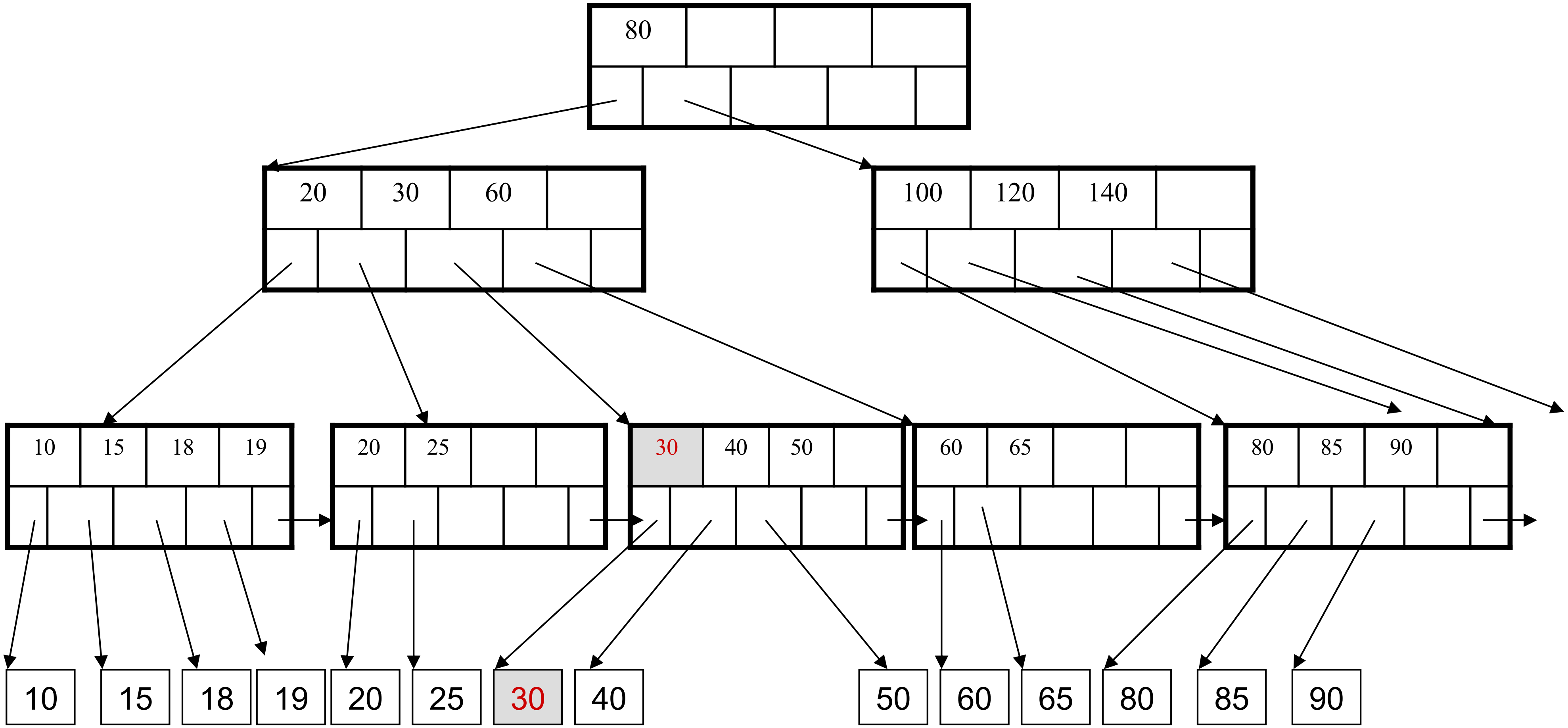
# Deletion in a B+ Tree

Delete (K, P)

- Find leaf where K belongs, delete
- Check for capacity
- If leaf below capacity, search adjacent nodes (left first, then right) for extra tuples and rotate them to new leaf
- If adjacent nodes at 50% full, merge
- Update and repeat algorithm on parent nodes if necessary

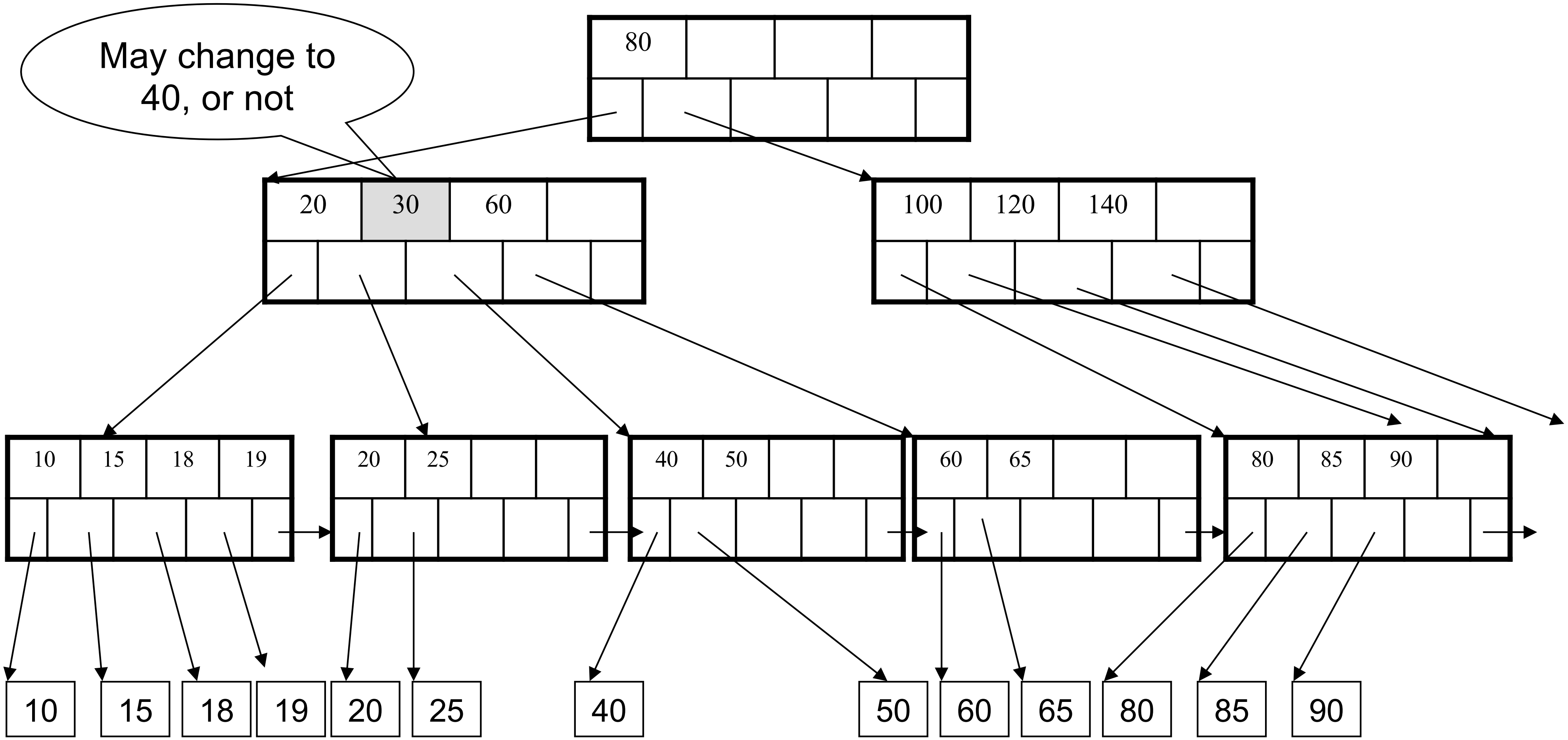
# Deletion from a B+ Tree

Delete 30



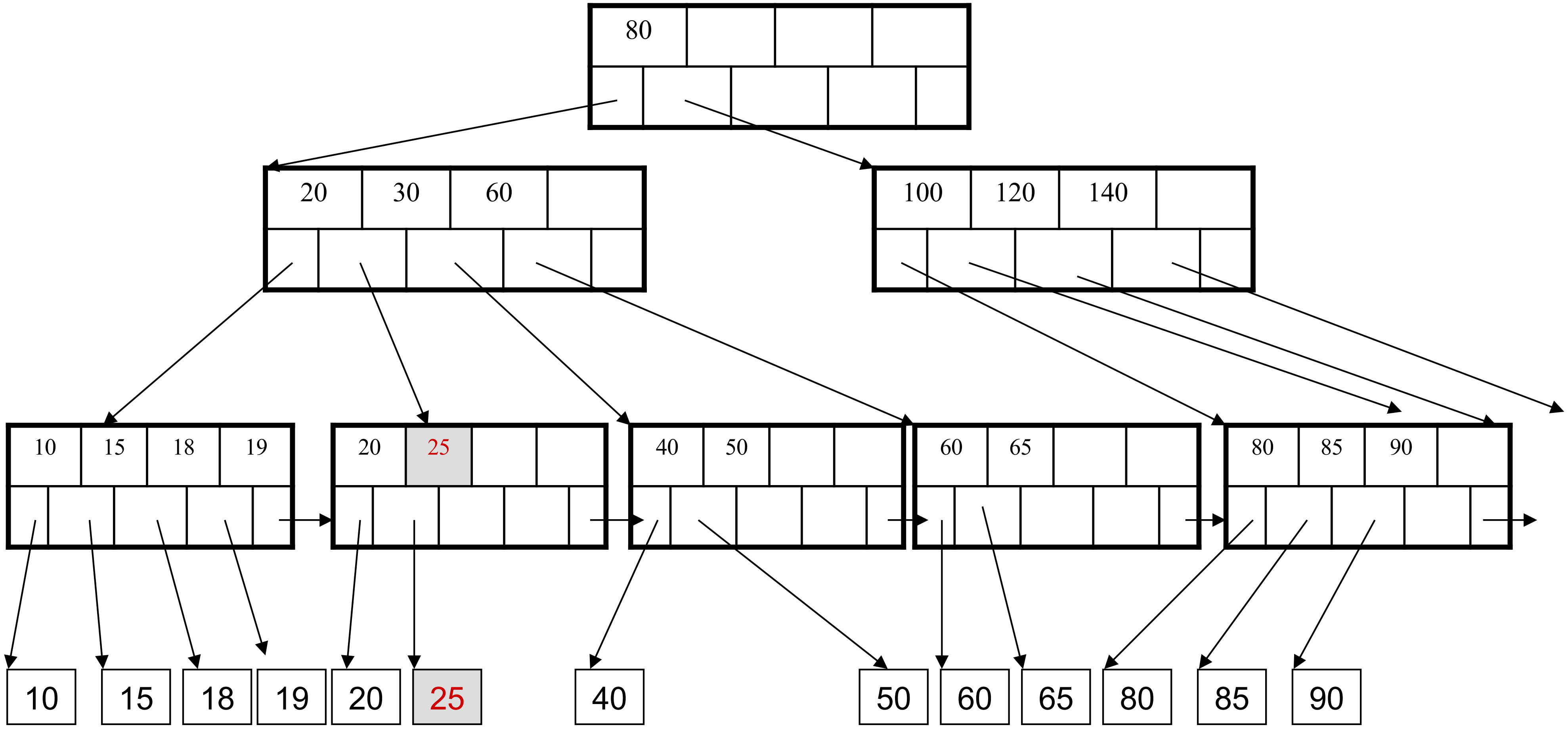
# Deletion from a B+ Tree

After deleting 30



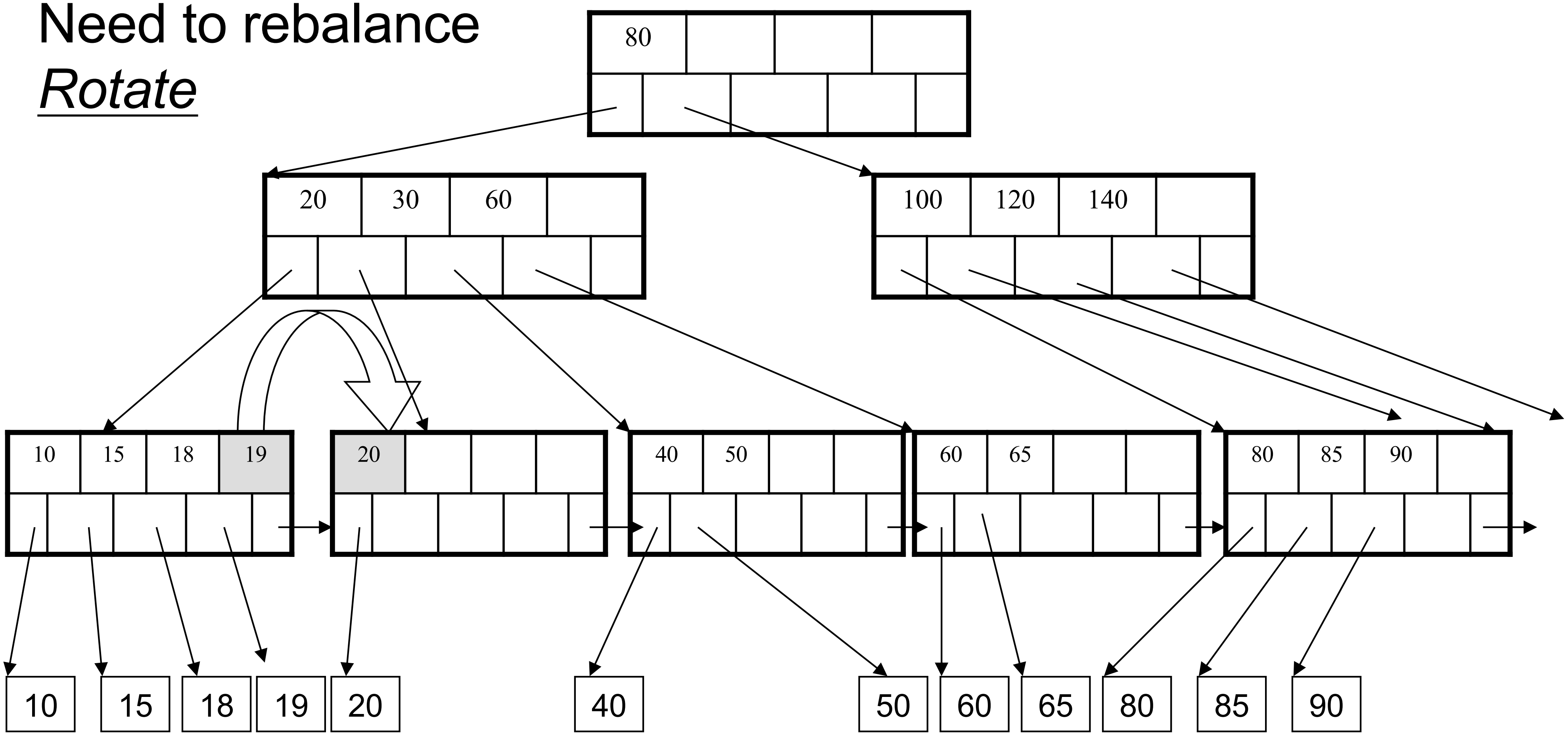
# Deletion from a B+ Tree

Now delete 25



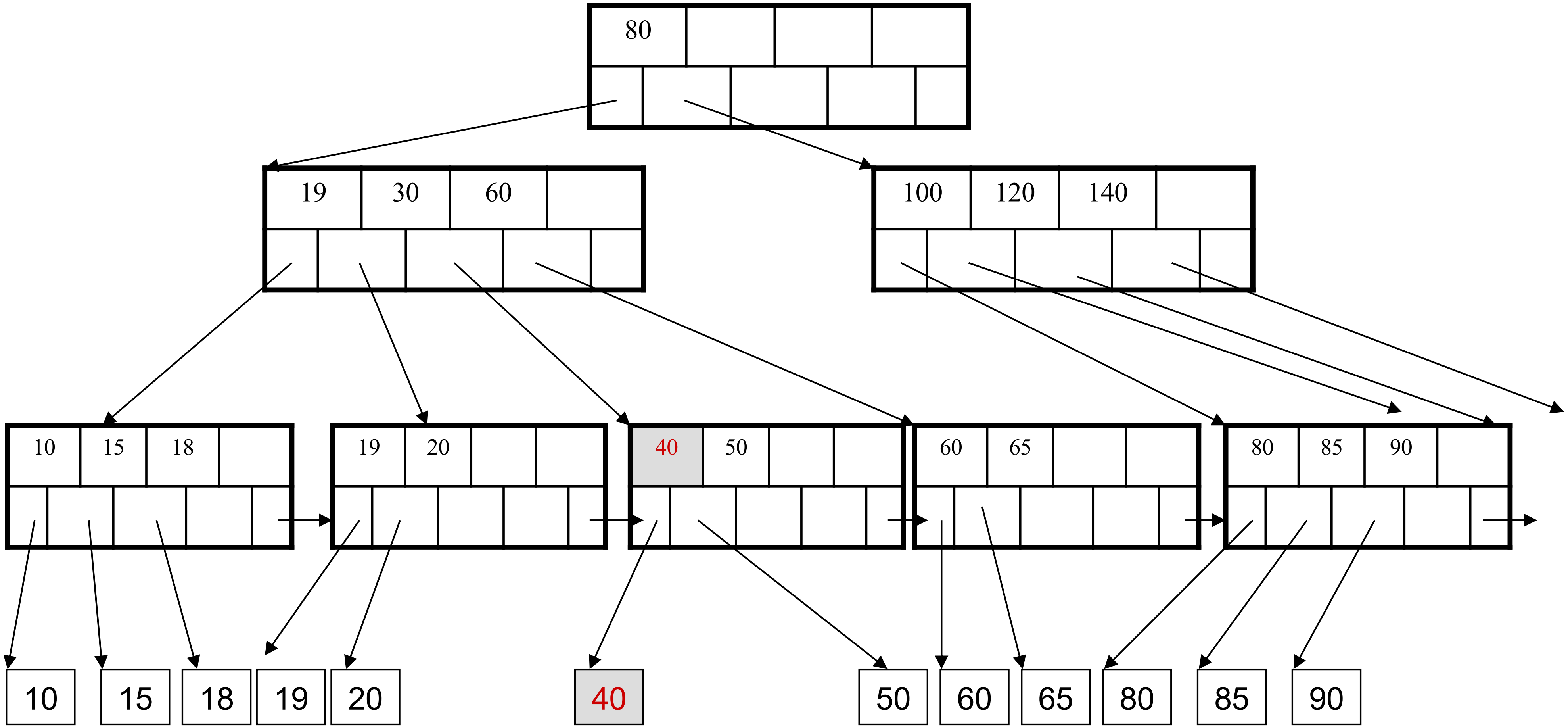
# Deletion from a B+ Tree

After deleting 25
Need to rebalance
*Rotate*



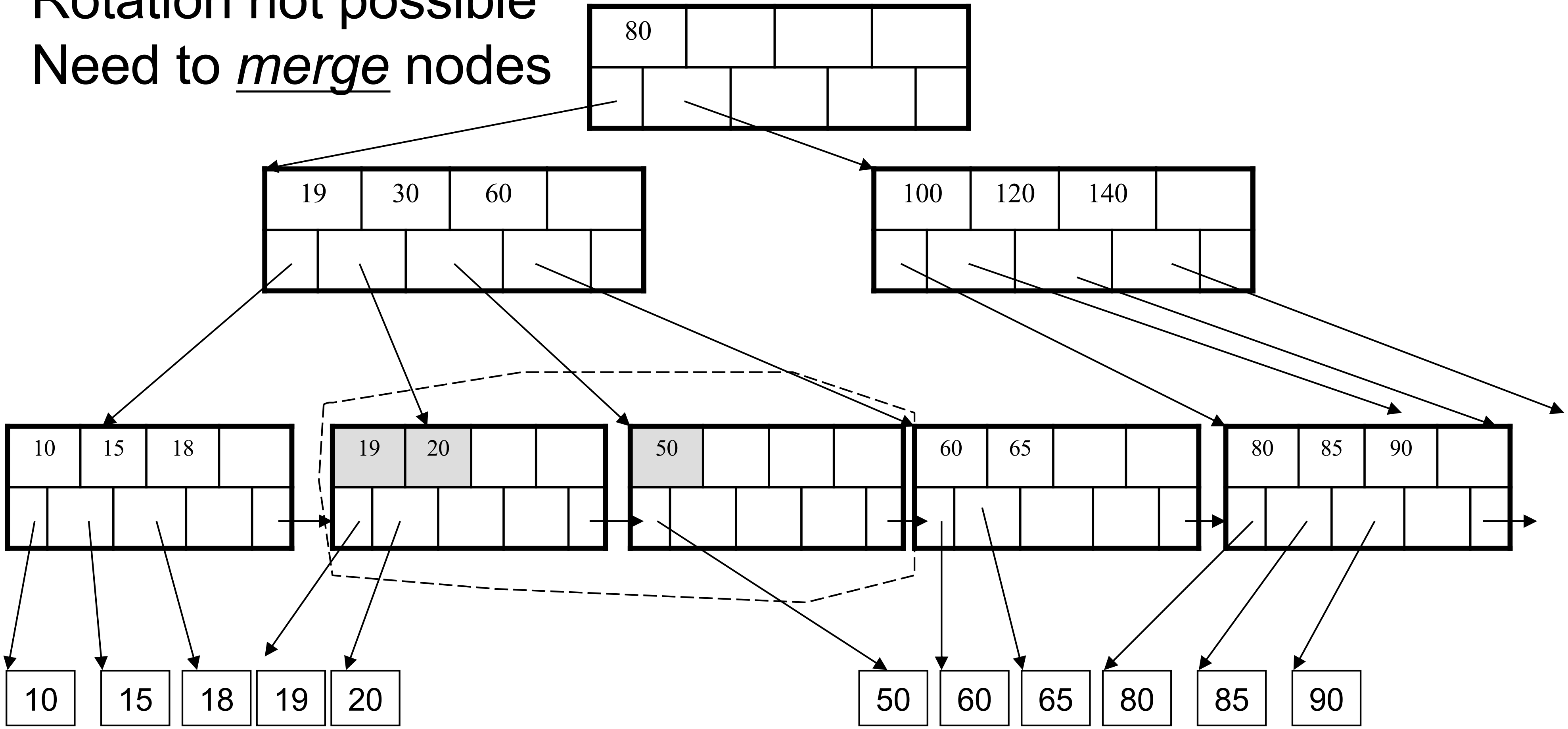
# Deletion from a B+ Tree

Now delete 40



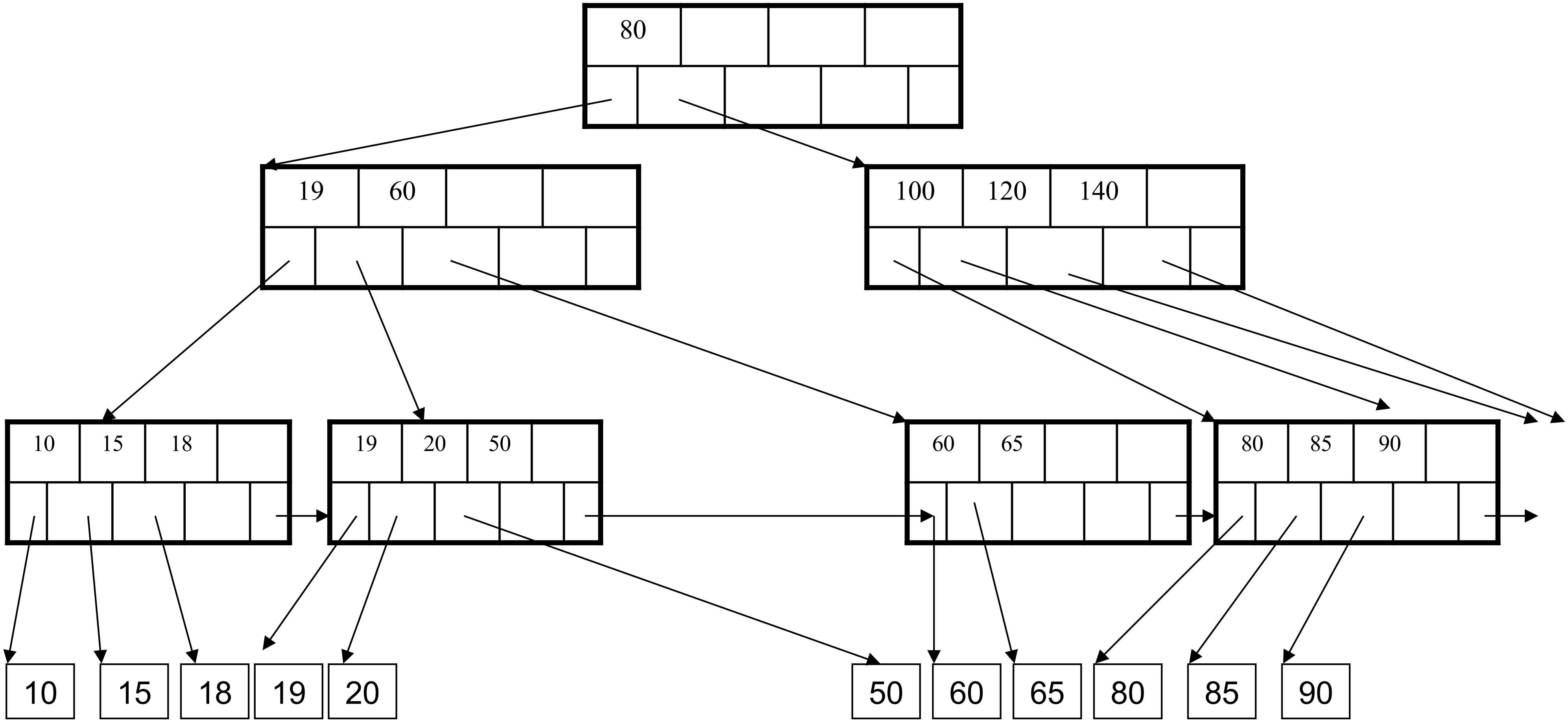
# Deletion from a B+ Tree

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