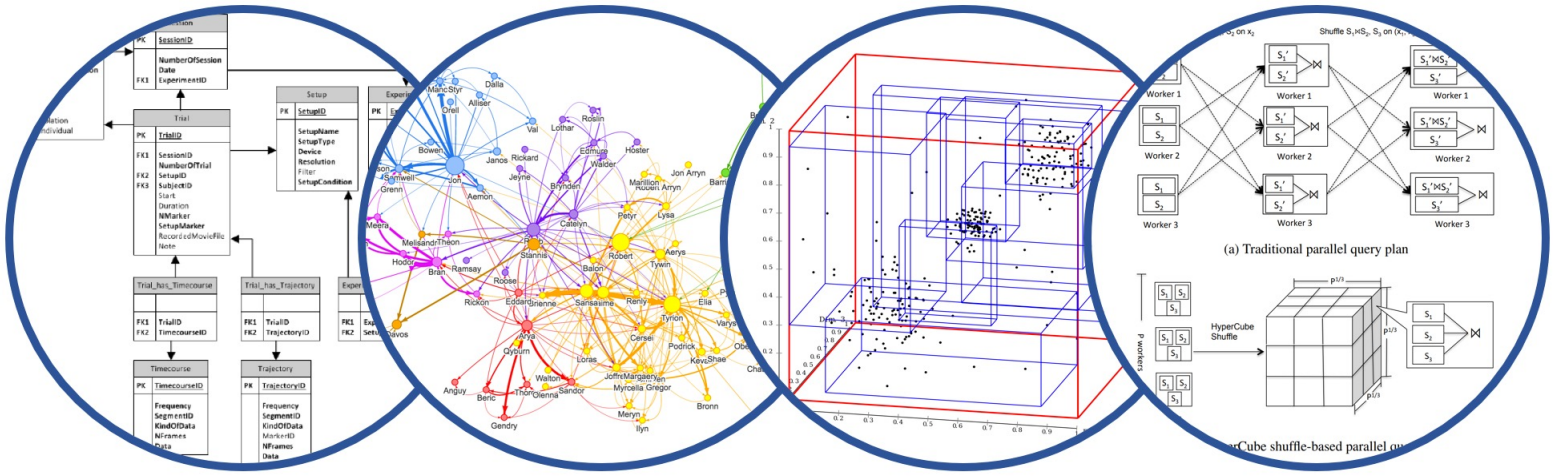



# Database System Internals

# Indexing

Paul G. Allen School of Computer Science and Engineering
University of Washington, Seattle

# Recap: Heap File

A sequence of pages (implementation in SimpleDB)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Data page | Data page | Data page | Data page | Data page | Data page | Data page | Data page |

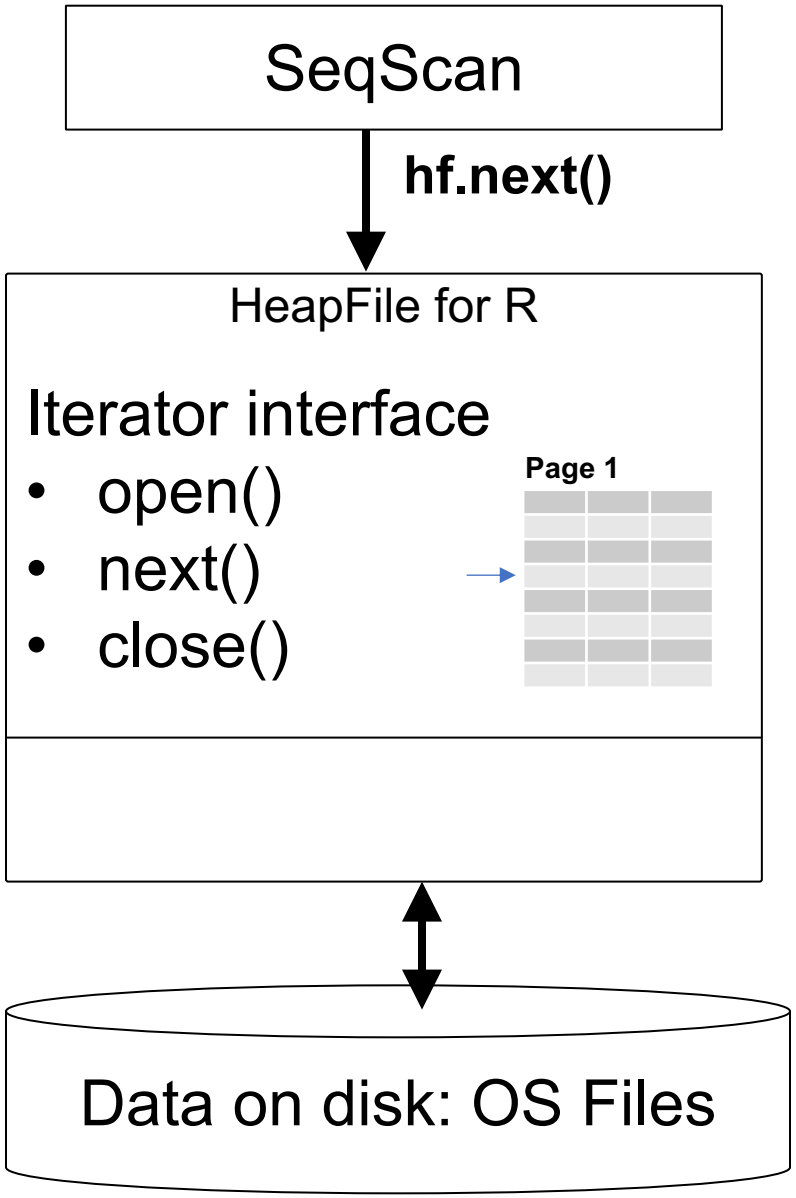
Some pages have space and other pages are full

Add pages at the end when need more space

Works well for small files

But finding free space requires scanning the file…

# Query Execution In SimpleDB



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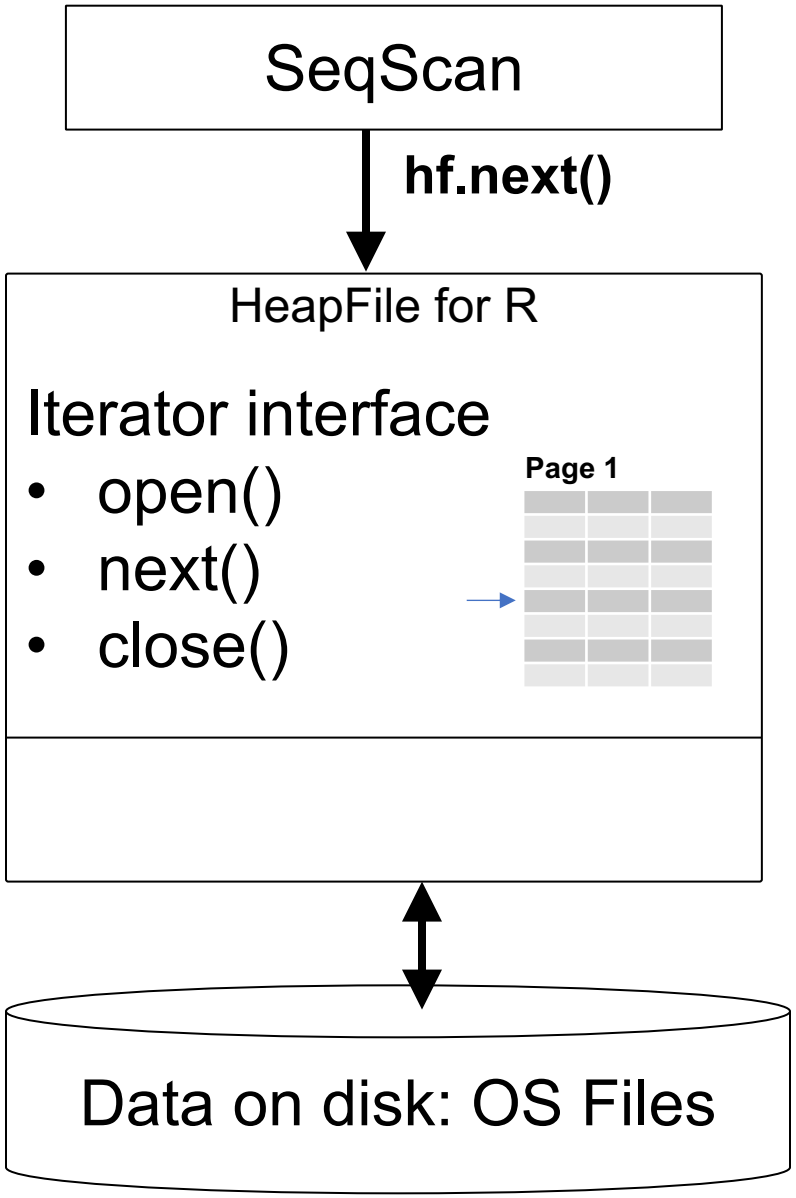

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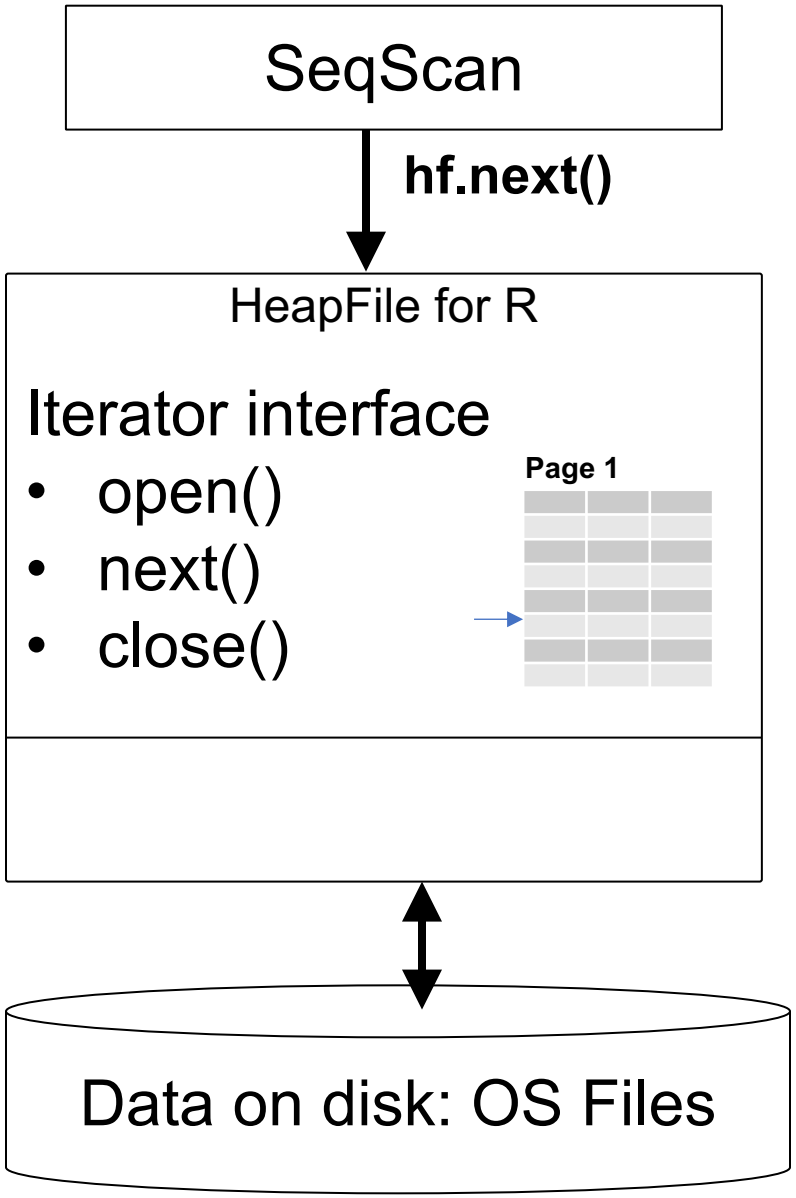

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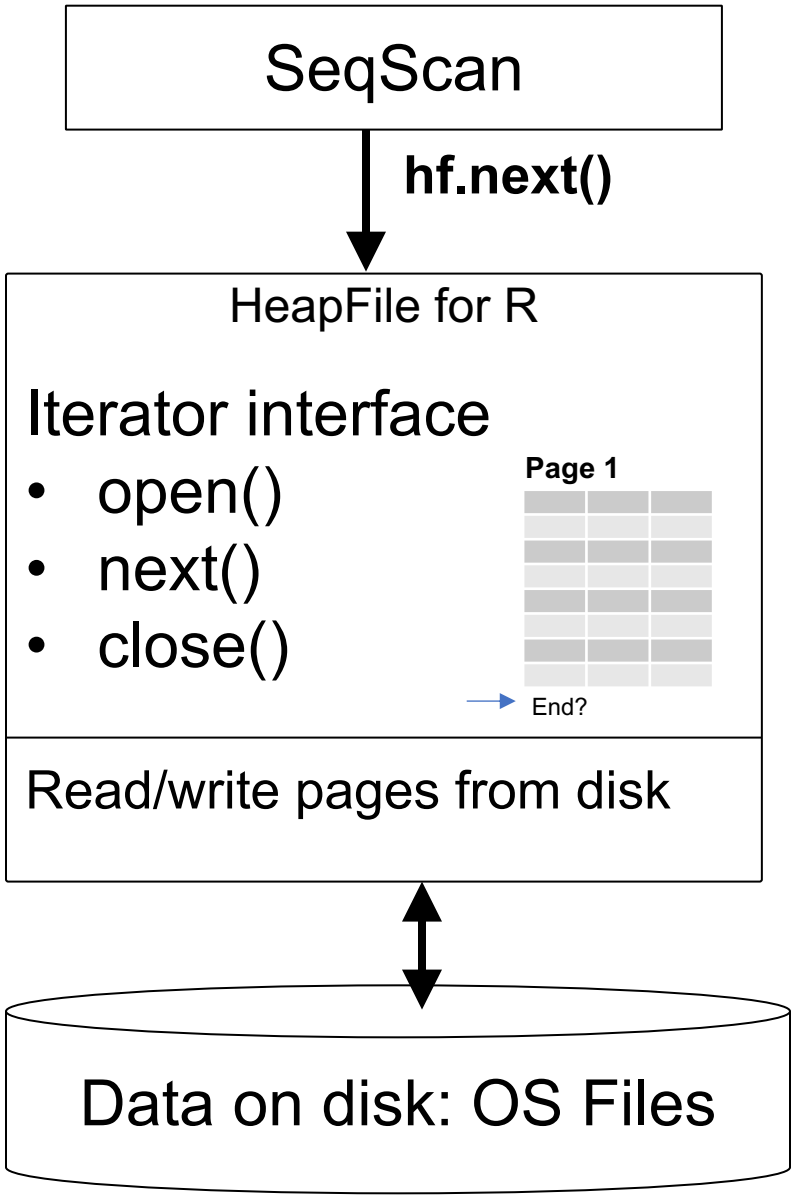

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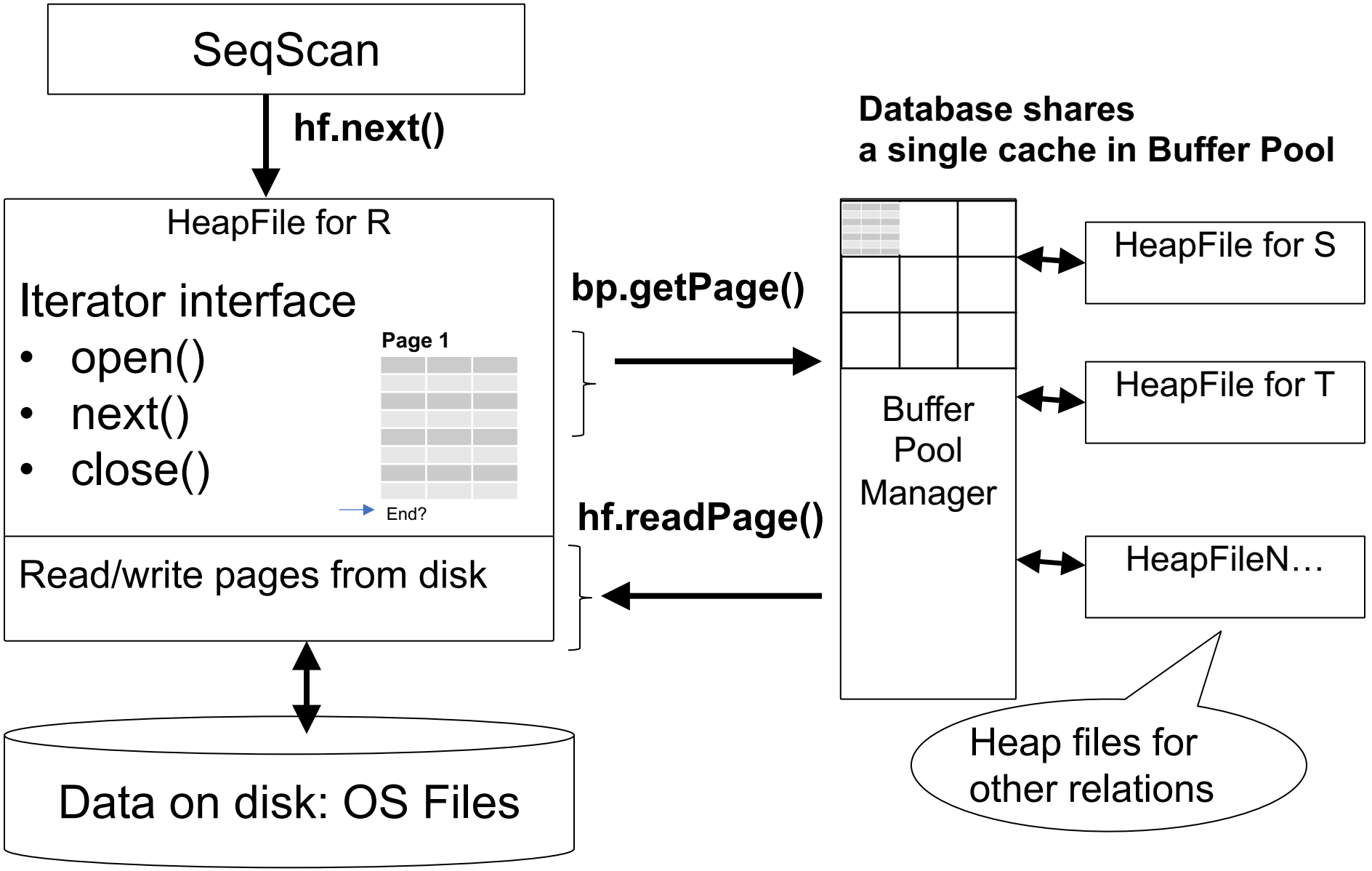

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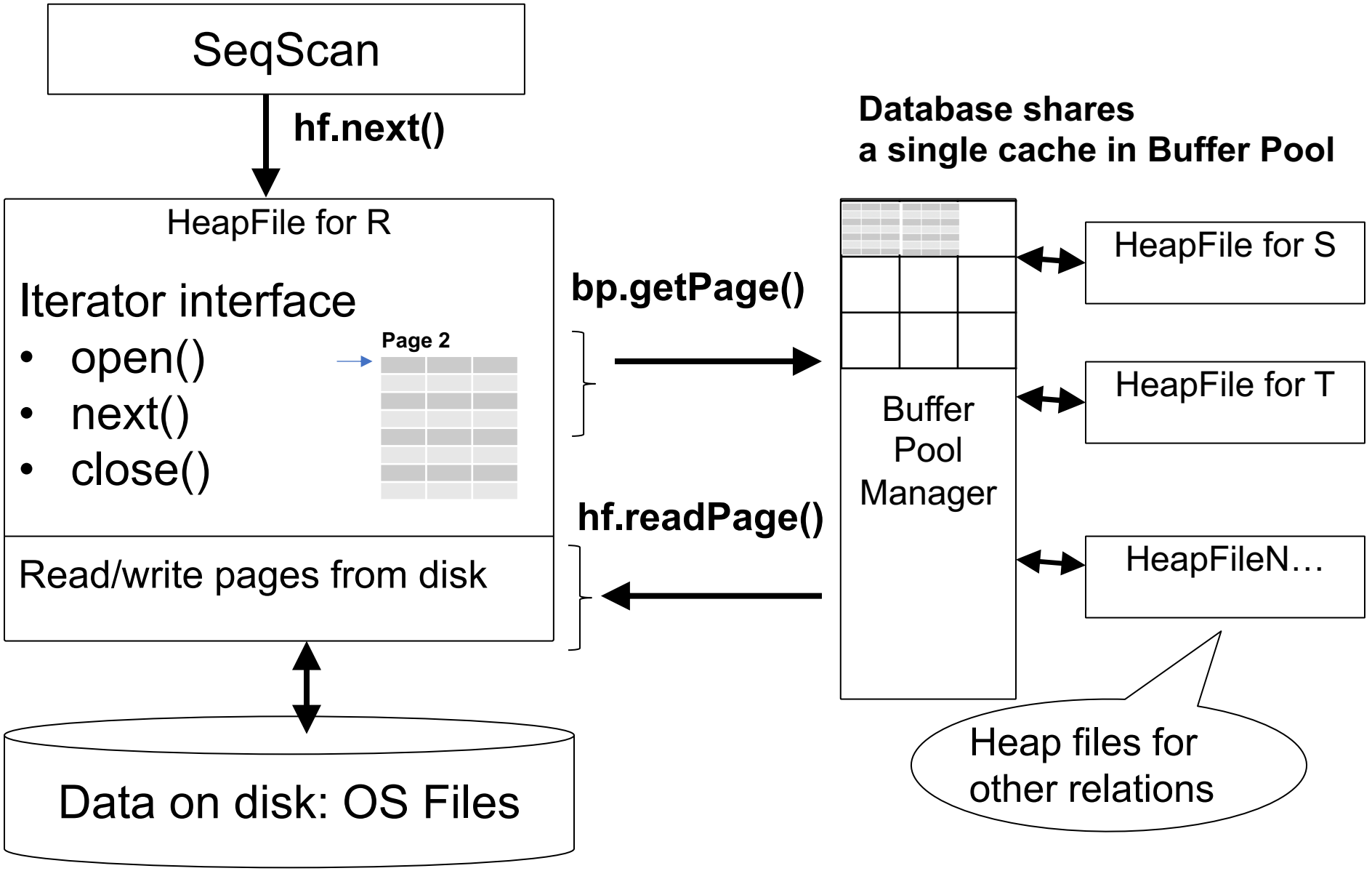
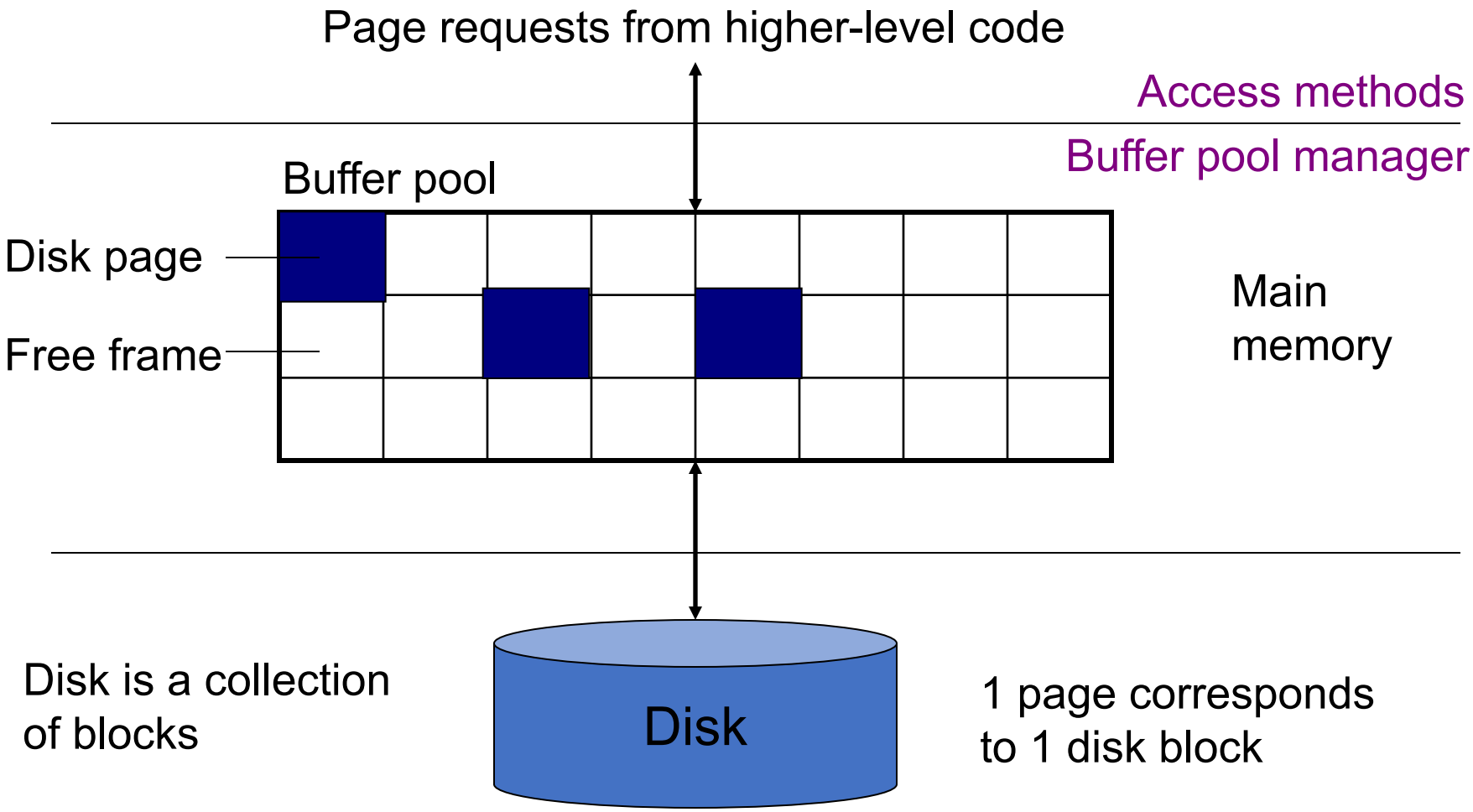


# Buffer Manager

- Brings pages in from memory and caches them
- Eviction policies
  - Random page (ok for SimpleDB)
  - Least-recently used (LRU)
  - 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



# Pushing Updates to Disk

- When inserting a tuple, HeapFile inserts it on a page but does not write the page to disk
- When deleting a tuple, HeapFile deletes tuple from a page but does not write the page to disk
- The buffer manager worries when to write pages to disk (and when to read them from disk)
- When need to add new page to file, HeapFile adds page to file on disk and then reads it through buffer manager

# 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
- **Get** a record with a given rid
  - Not necessary for sequential scan operator
  - But used with indexes
- **Scan** all records in the file

# Basic Access Method: Heap File

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  - Not necessary for sequential scan operator
  - But used with indexes
- **Scan** all records in the file

Next: how to scan only *some* records

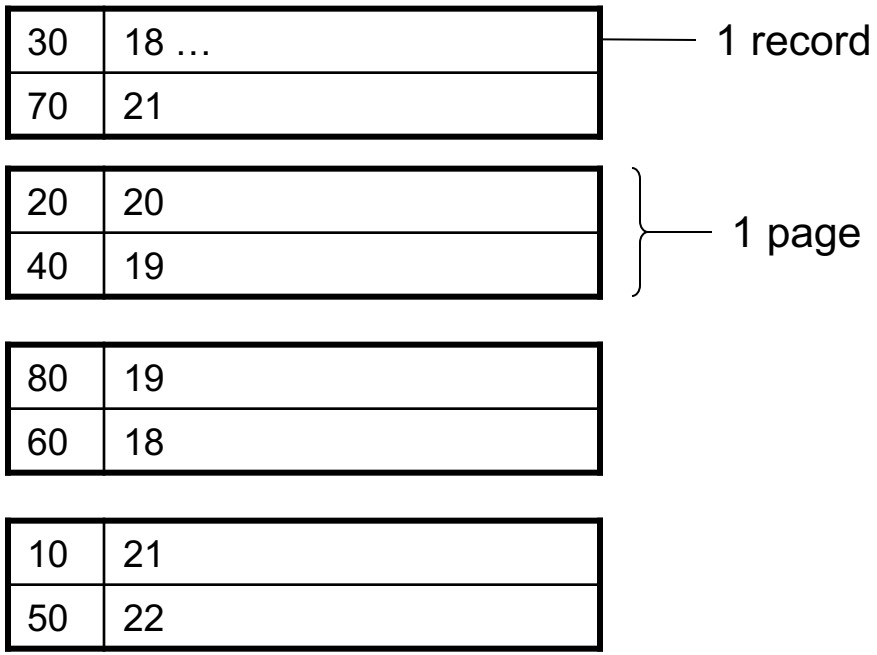
# Access by Attribute Value

- Scan all Suppliers where city='Seattle'
- Scan all Students with GPA > 3.5
- Scan all Students with SID = 12345 // just one

# 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 where sid =12345

  How many pages must we read? (avg or otherwise.)

# Heap File Search Example

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- Find all students where age > 20
  - How many pages must we read? (avg or otherwise.)

- Can we do better?

# Heap File Search Example

- 10,000 students
- 10 student records per page
- Total number of pages: 1,000 pages

- Find student where sid =12345
  - Must read on average 500 pages

- Find all students where age > 20
  - Must read all 1,000 pages

- Can we do better?

# Sorted File (a.k.a. Sequential File)

File sorted on an attribute, usually on primary key

```
Student(sid: int, age: int, …)
```

| id | age |
|---|---|
| 10 | 21 … |
| 20 | 20 |

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

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

| | |
|---|---|
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# Sequential File Example

- Total number of pages: 1,000 pages

- Find student where sid=12345
  - How many pages do we need to read?

# Sequential File Example

- Total number of pages: 1,000 pages

- Find student where sid=12345
  - How many pages do we need to read?
  - Binary search: read $\log_2(1{,}000) \approx 10$ pages

# Limitations of Sorted Files

We want to support these kinds of queries:

- Find student where sid=12345
- Find students where age > 20
- Insert a new student

What are the limitations of using a sorted file?

# Creating Indexes in SQL

```
CREATE  TABLE  Student(sid int, age int, gpa real, …);
```

```
select *
from Student
where sid=12345
```

# Creating Indexes in SQL

```
CREATE  TABLE  Student(sid int, age int, gpa real, …);
```

```
CREATE  INDEX s_sid ON Student(sid)
```

```
select *
from Student
where sid=12345
```

# Creating Indexes in SQL

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```
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```

```
select *
from Student
where sid=12345
```

```
CREATE  INDEX s_age ON Student(age)
```

# Creating Indexes in SQL

```
CREATE  TABLE  Student(sid int, age int, gpa real, …);
```

```
CREATE  INDEX s_sid ON Student(sid)
```

```
select *
from Student
where sid=12345
```

```
CREATE  INDEX s_age ON Student(age)
```

```
select *
from Student
where age > 25
```

# Outline

- Index structures
- Hash-based indexes

} Today

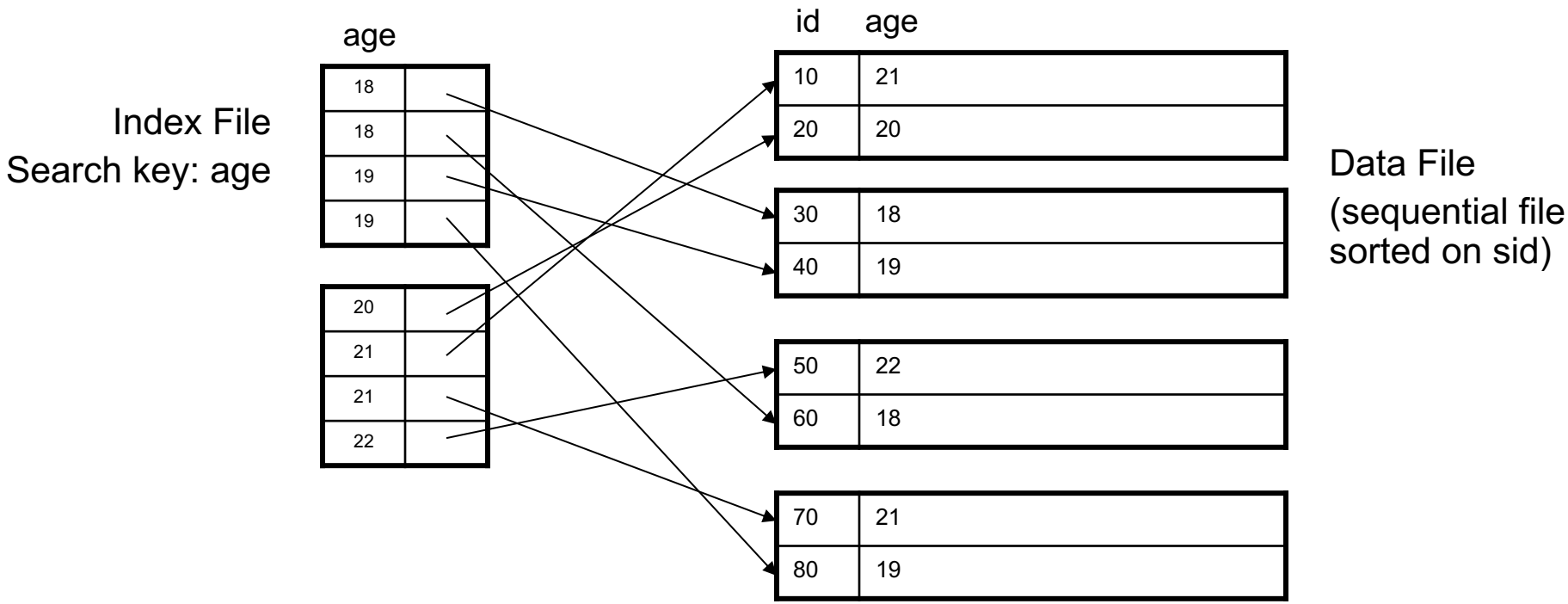
- B+ trees

} Next time

# Indexes

- **Index:** separate file with fast access by "search key" value
- Contains pairs of the form (key, RID)

- Indexes are access methods! Same API as Heap Files



# Indexes

- **Search key** = can attribute or set of attributes
  - not the same as the primary key; not a key
- **Index** = collection of data entries
- **Data entry** for key k can be:
  - (k, RID)
  - (k, list-of-RIDs)
  - Record with key k; "clustered" or "primary" index

# Different Types of Files

Imagine one relation, say Student

- The Student file can be:
  - Heap file (tuples stored without any order)
  - Sequential file (tuples sorted on some attribute(s))
  - Clustered (primary) index file (relation+index)

- There can be several unclustered (secondary) index files that store (key,rid) pairs

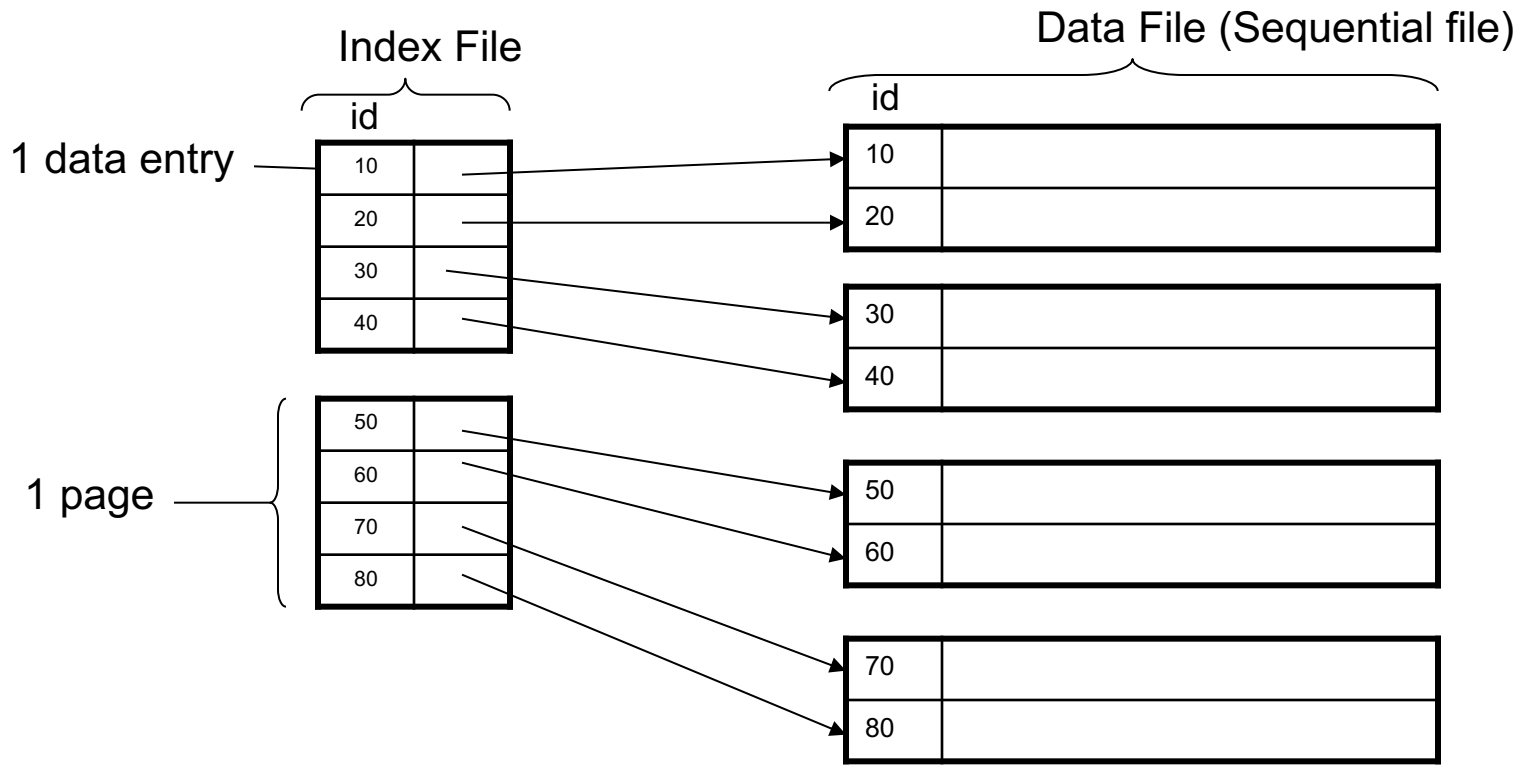
# How Indexes Help

We want to support these kinds of queries
Assume Student = a heap file

- Find student where sid=12345
  - Use an index on Student(sid)
- Find students where age > 20
  - Use an index on Student(age)
- Insert a new student
  - Insert in the Student heap file – easy
  - Insert in indexes Student(sid), Student(age) – will discuss

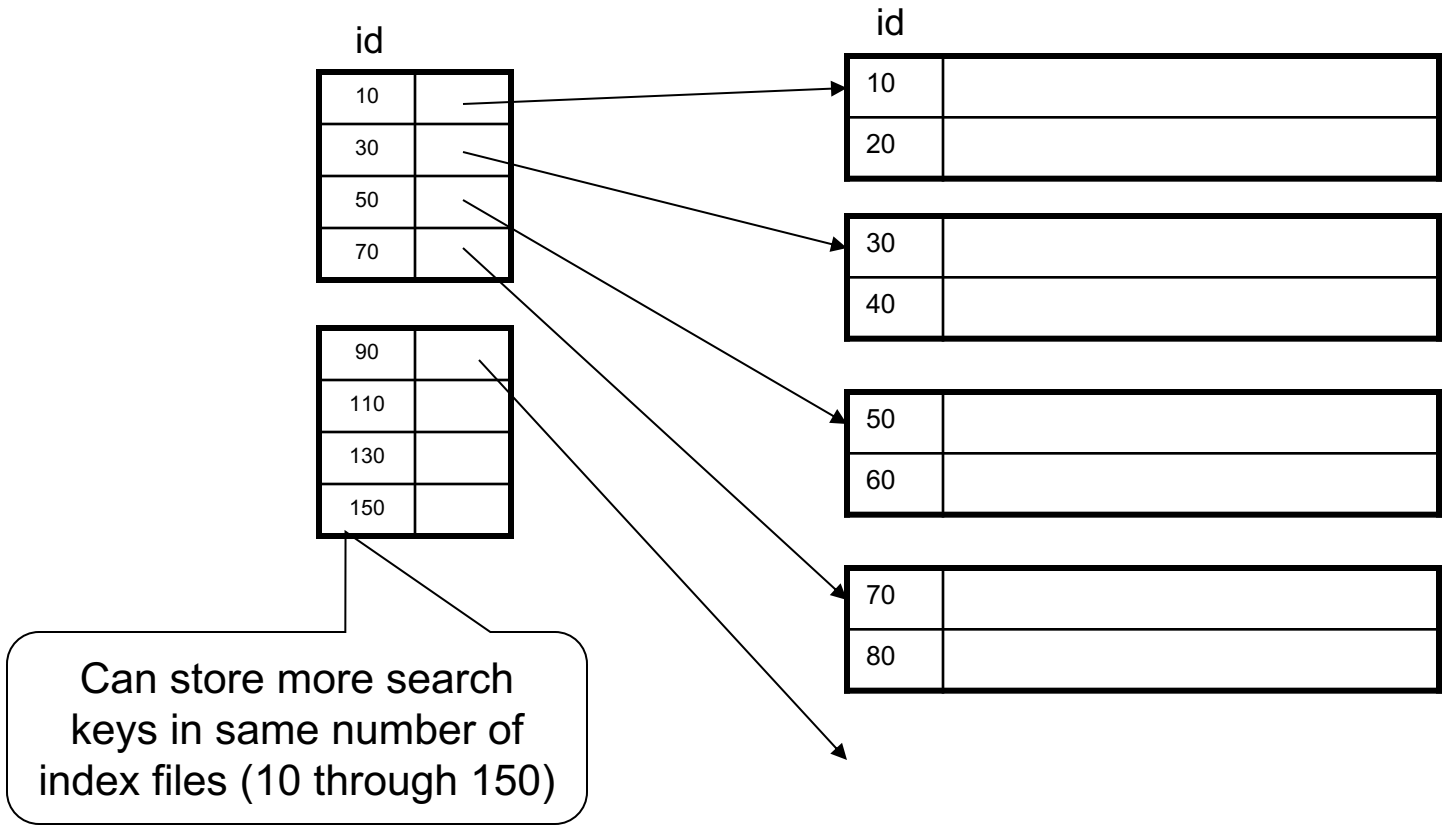
# Clustered Index (aka Primary Index)

- Records in data file have same order as in index
- *Dense* index: sequence of (key,rid) pairs



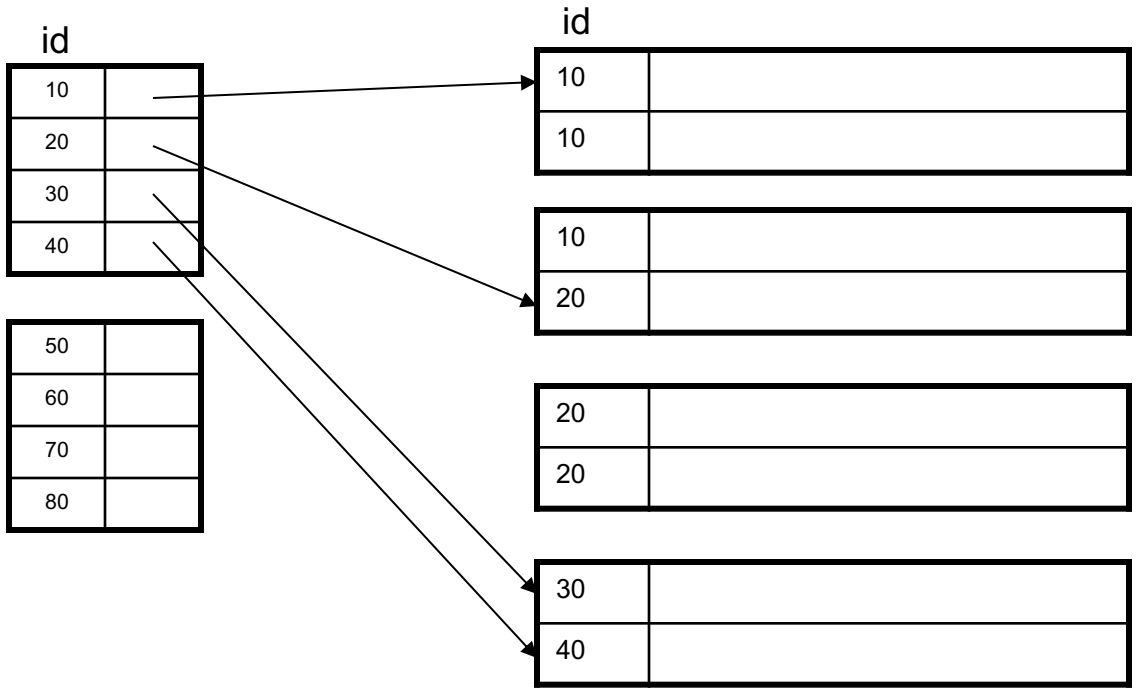
# Clustered Index (aka Primary Index)

- Records in data file have same order as in index
- *Sparse* index: store a subset of (key,rid) pairs



# Clustered Index with Duplicate Keys

- Dense index:



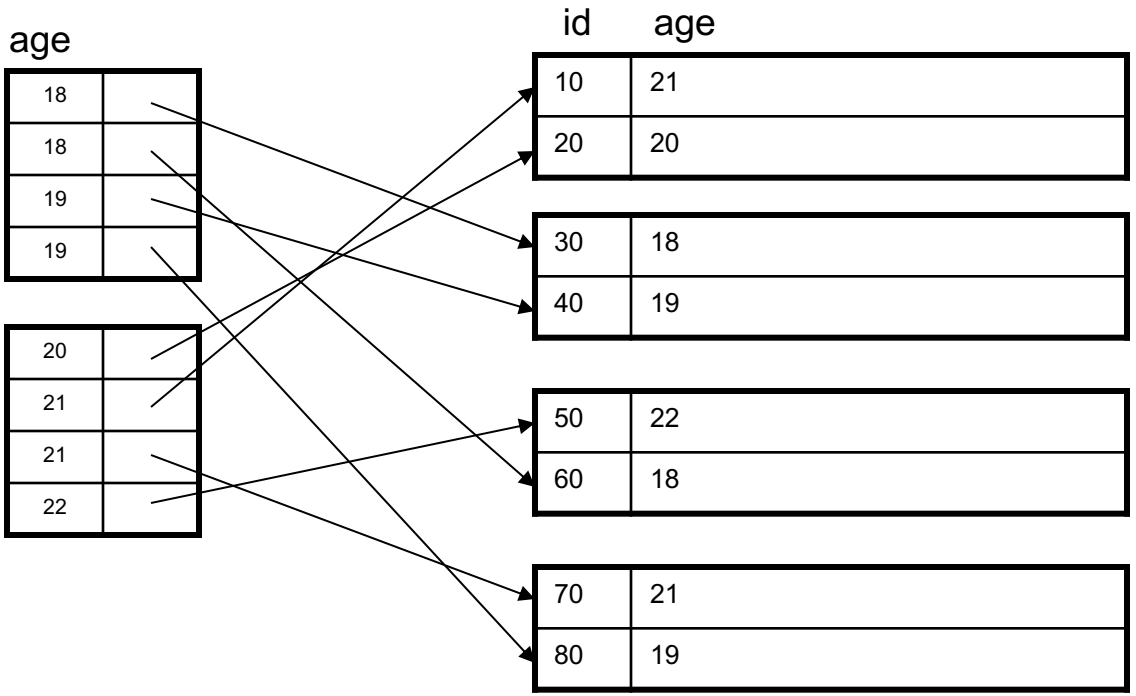
# Clustered Index: Back to Example

- Assume entire index fits in main memory

- Find student where sid=12345
  - Index (dense or sparse) points directly to the page
  - Read only 1 page from disk
- Find all students where age > 20
  - Add a second index…

# Secondary Indexes

- Do not determine placement of records in data files



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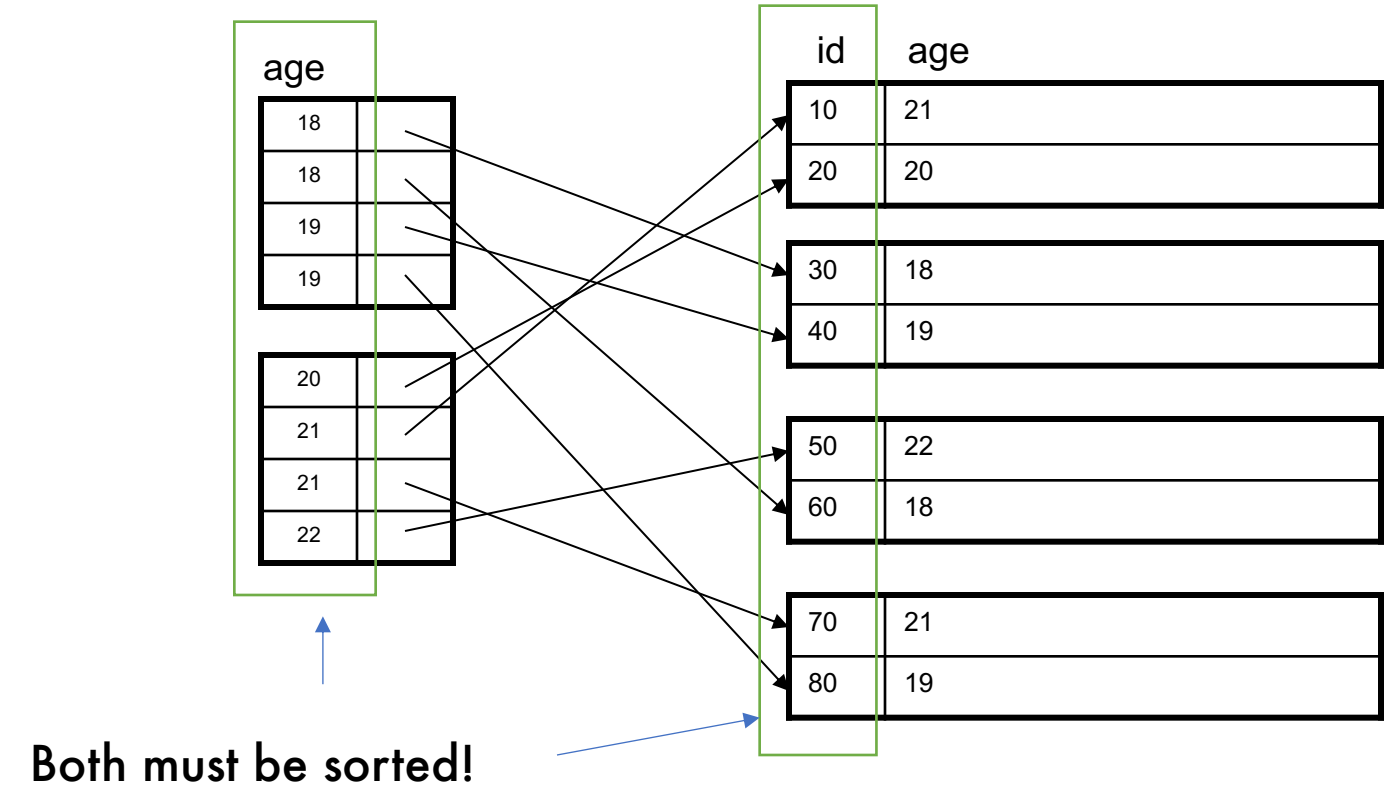
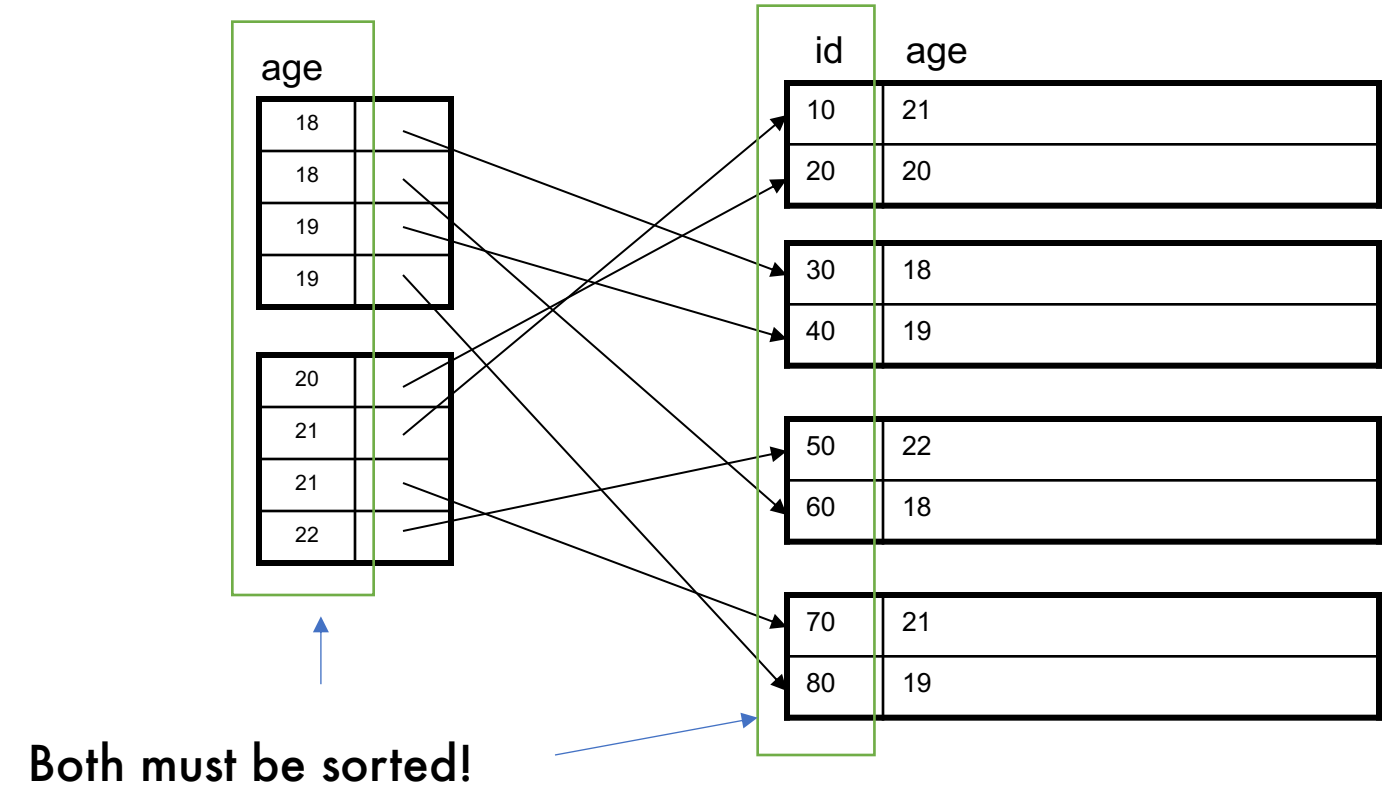


# Secondary Indexes

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



# The Confusing Terminology of Indexes…

- Clustered index:
  - Means: keys close in the index are also close in the data
  - Can co-exist with the data file (quite common)
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# The Confusing Terminology of Indexes…

- Clustered index:
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  - Can co-exist with the data file (quite common)
  - Can have only one clustered index
  - Sometimes called "primary index"
- Unclustered index:
  - Means: order in the index and order in the data differ
  - Always a separate file
  - Can have as many unclustered indexes as we want
  - Sometimes called "secondary index"

# Index Organization

- How would you design the index data structure?

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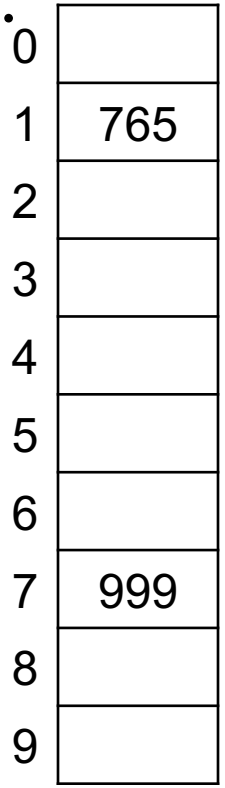
  - B+ tree

# BRIEF Review of Hash Tables

Arrays are *very* efficient:

- Find(T[7])



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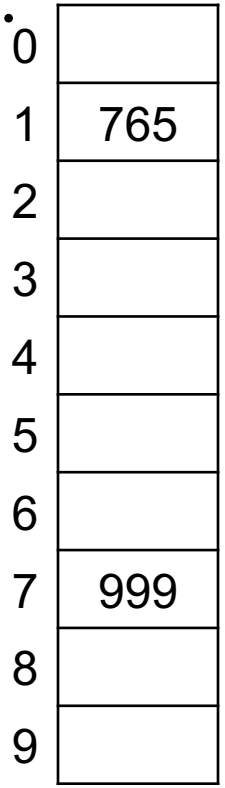
- Find(T[7])
- Set T[3] := 234



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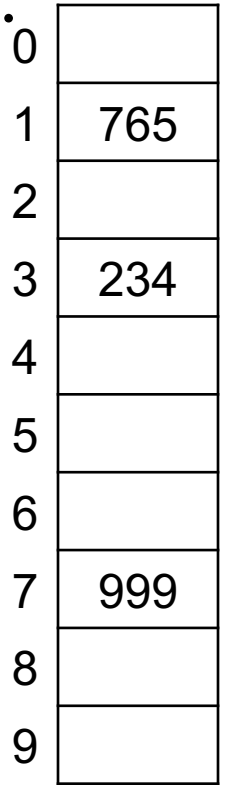

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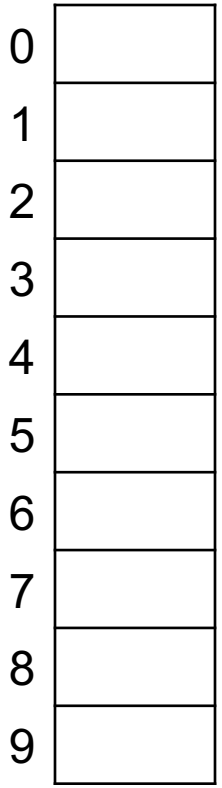

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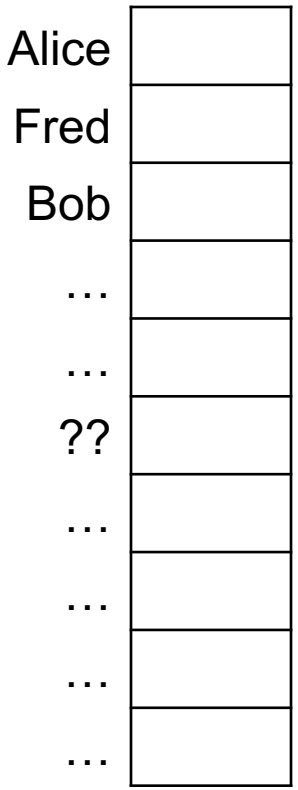

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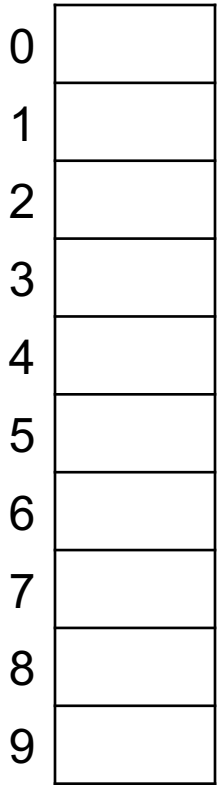
A (naïve) hash function:

h(k) = sum(k) mod 10



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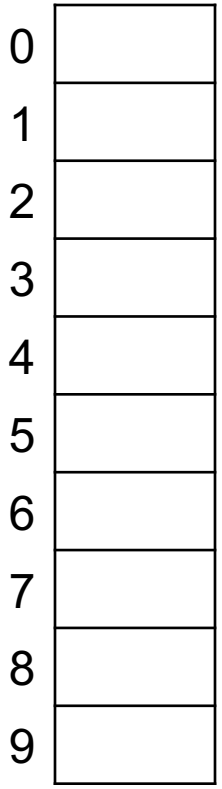


Example: h("Fred") =
= (ascii("F")+ascii("r")+...) mod 10
= (70 + 114 + 101 + 100) mod 10
= 5

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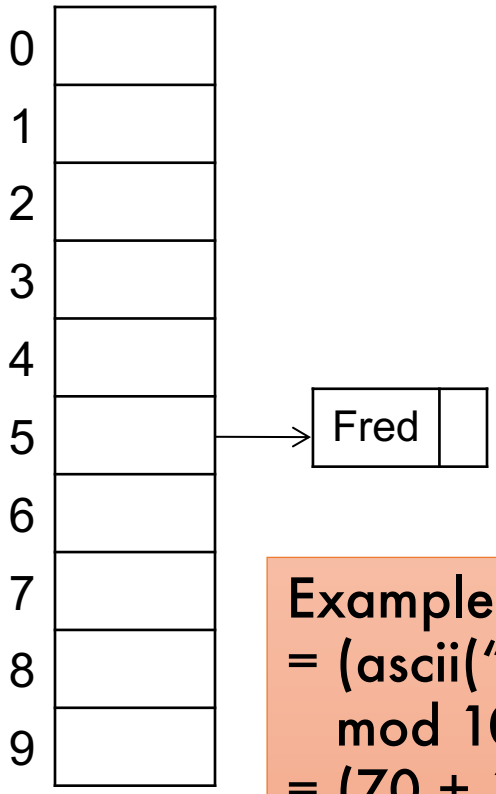


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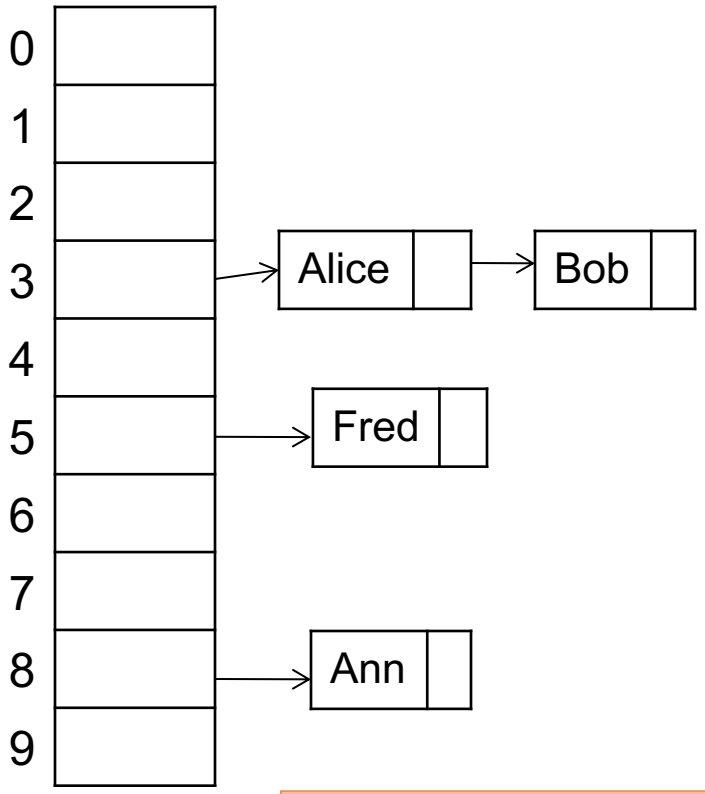


h("Alice") = h("Bob") = 3
Called *collisions*

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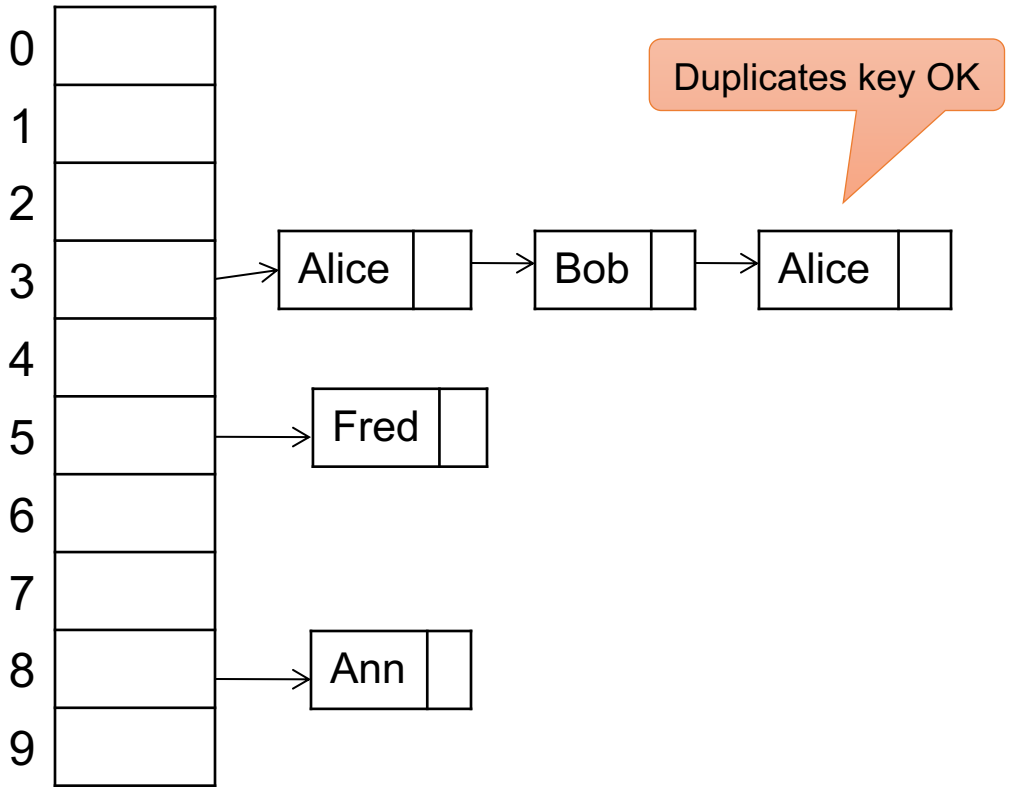

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Operations:

find(Bob) = ??

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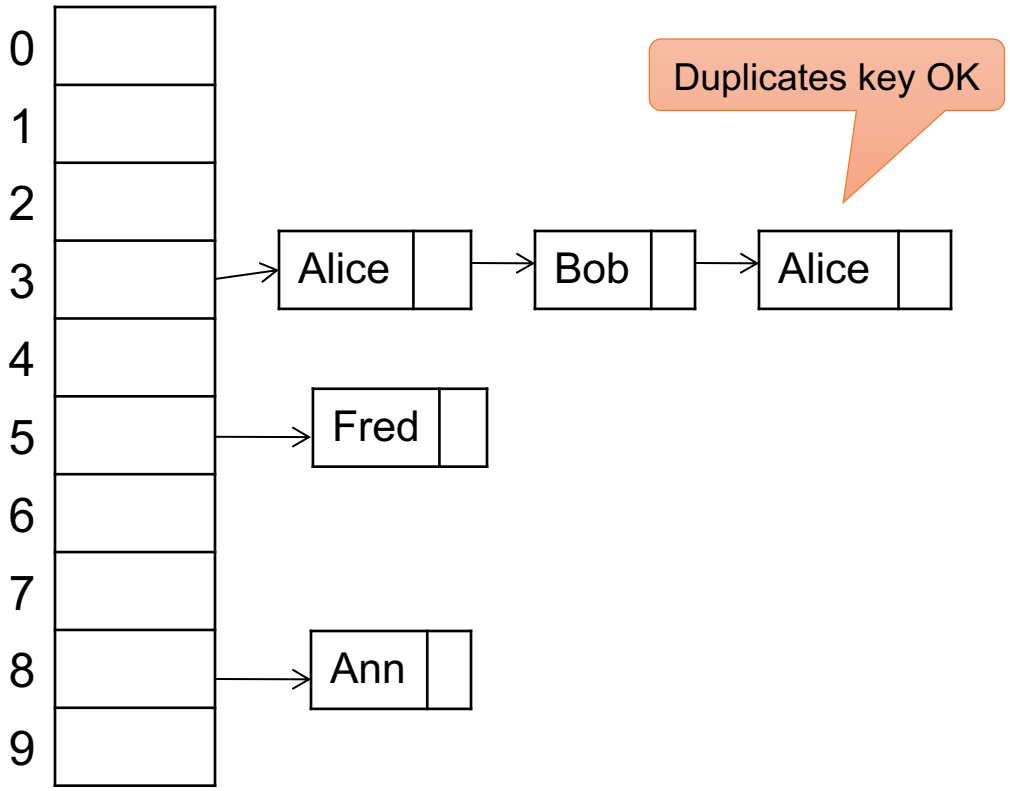

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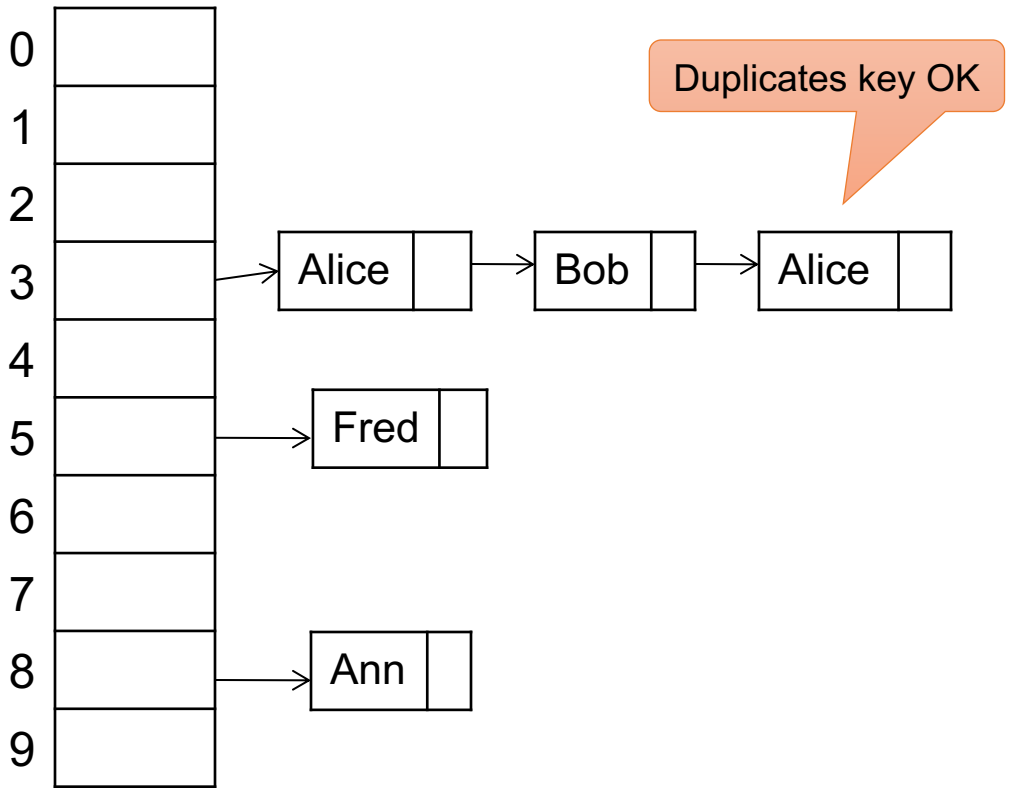


Operations:

find(Bob) = ??

insert(Jon) = ??

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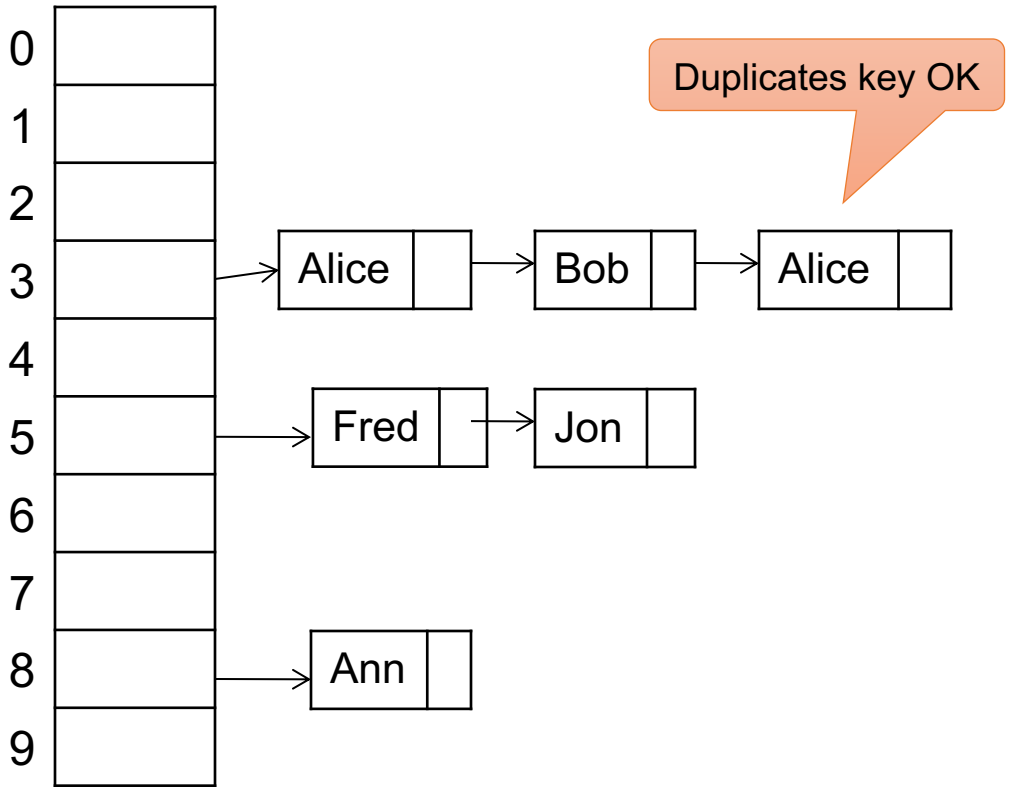

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A (naïve) hash function:

$$h(k) = \text{sum}(k) \bmod 10$$

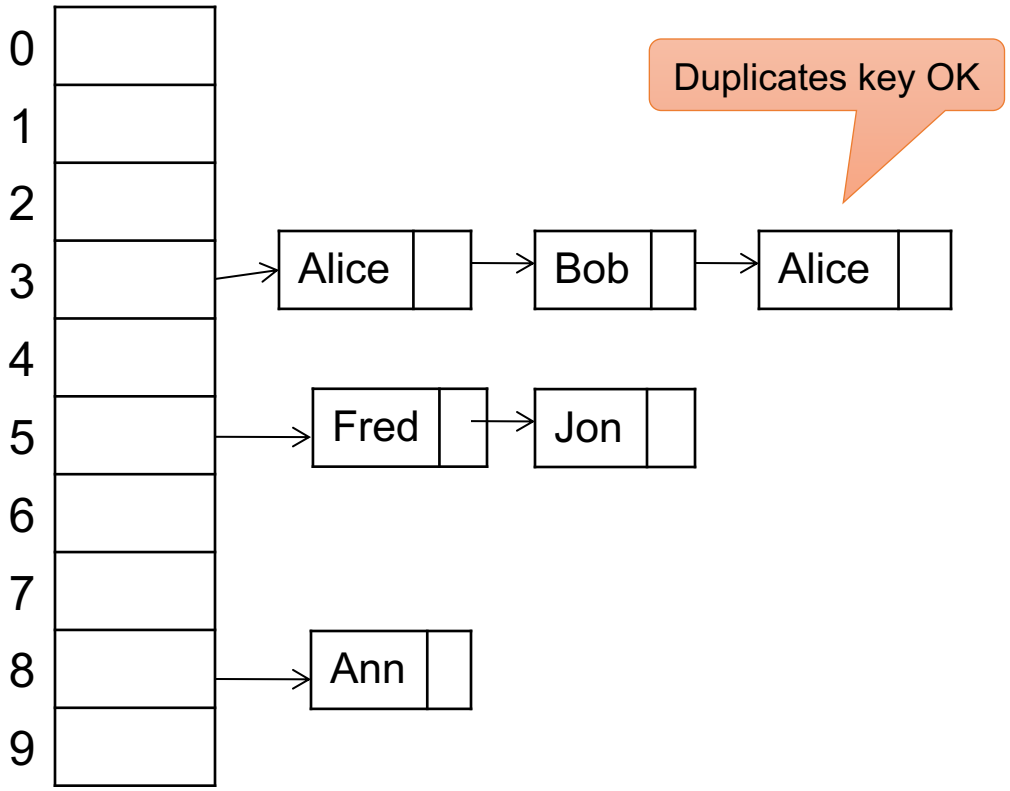
Operations:

find(Bob) = ??

insert(Jon) = ??

delete(Ann) = ??

Separate chaining:



# BRIEF Review of Hash Tables

- insert(k, v) = inserts a key k with value v
  - Duplicate k's may be OK or may not be OK

- find(k) = returns the value v associated to k,
  or the ***list*** of all values associated to k

- delete(k)

# Discussion of Hash Tables

- Hash function:
  - Should distribute values uniformly
  - Never write your own! (why is x mod 10 bad?)
    Use a standard library function
  - Best: concatenate with fixed, random seed (in class)
- Hash table:
  - Size of table: large enough to avoid collisions
  - Typically: size of table ≈ size of data
  - Why not make it small? Why not make it big?
  - Problem: hash table allocated statically, at creation
  - Book describes solutions to increase size dynamically

# Hash-Based Index

Good for point queries but not range queries

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

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

| | |
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| | |
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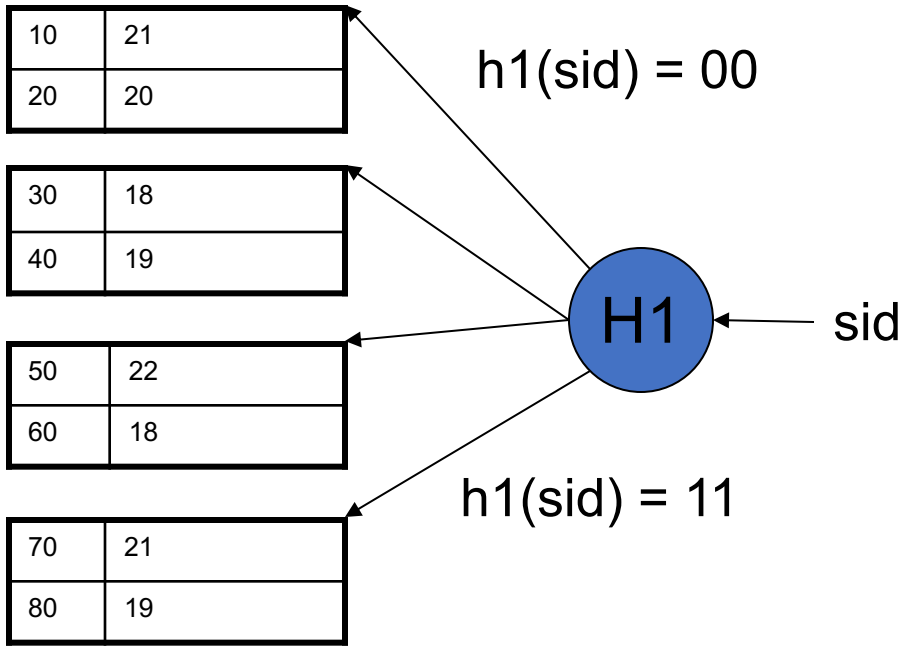
Data File

# Hash-Based Index

Good for point queries but not range queries




Data File
Primary hash-based index

# Hash-Based Index

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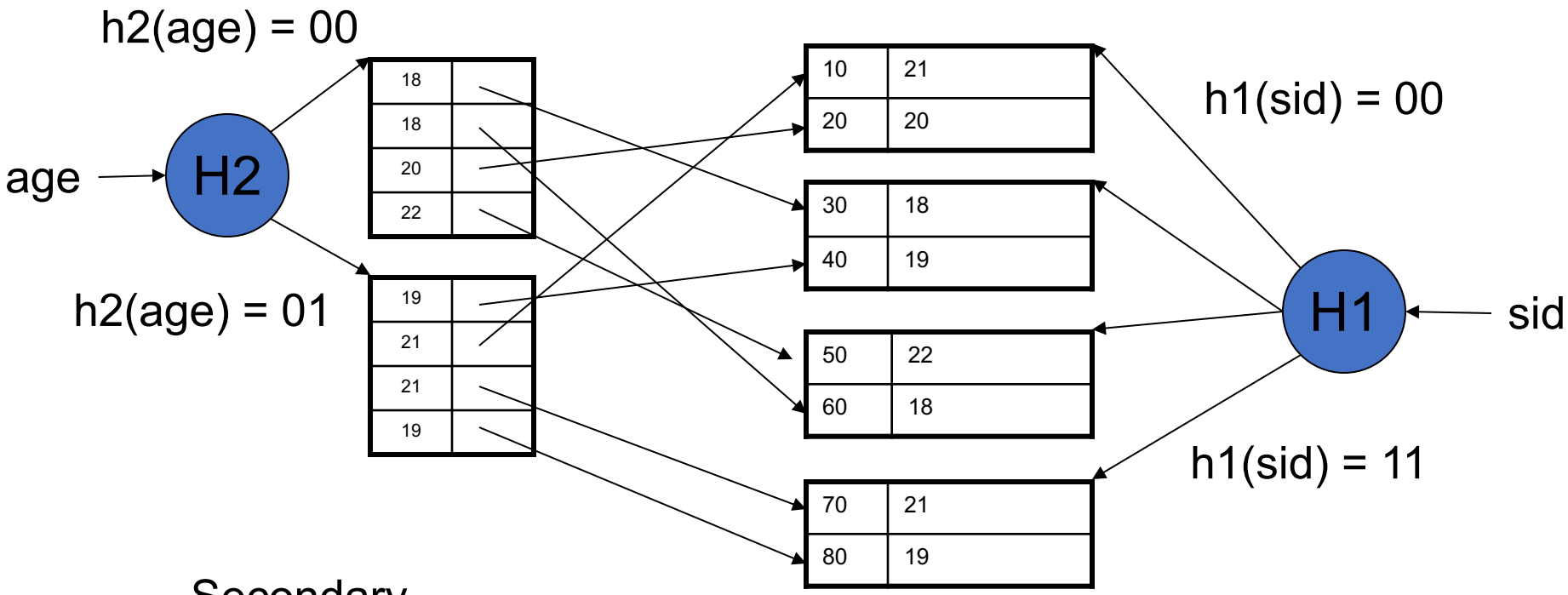



Secondary
hash-based index
(age, rid) pairs

Data File
Primary hash-based index

# B+ Trees

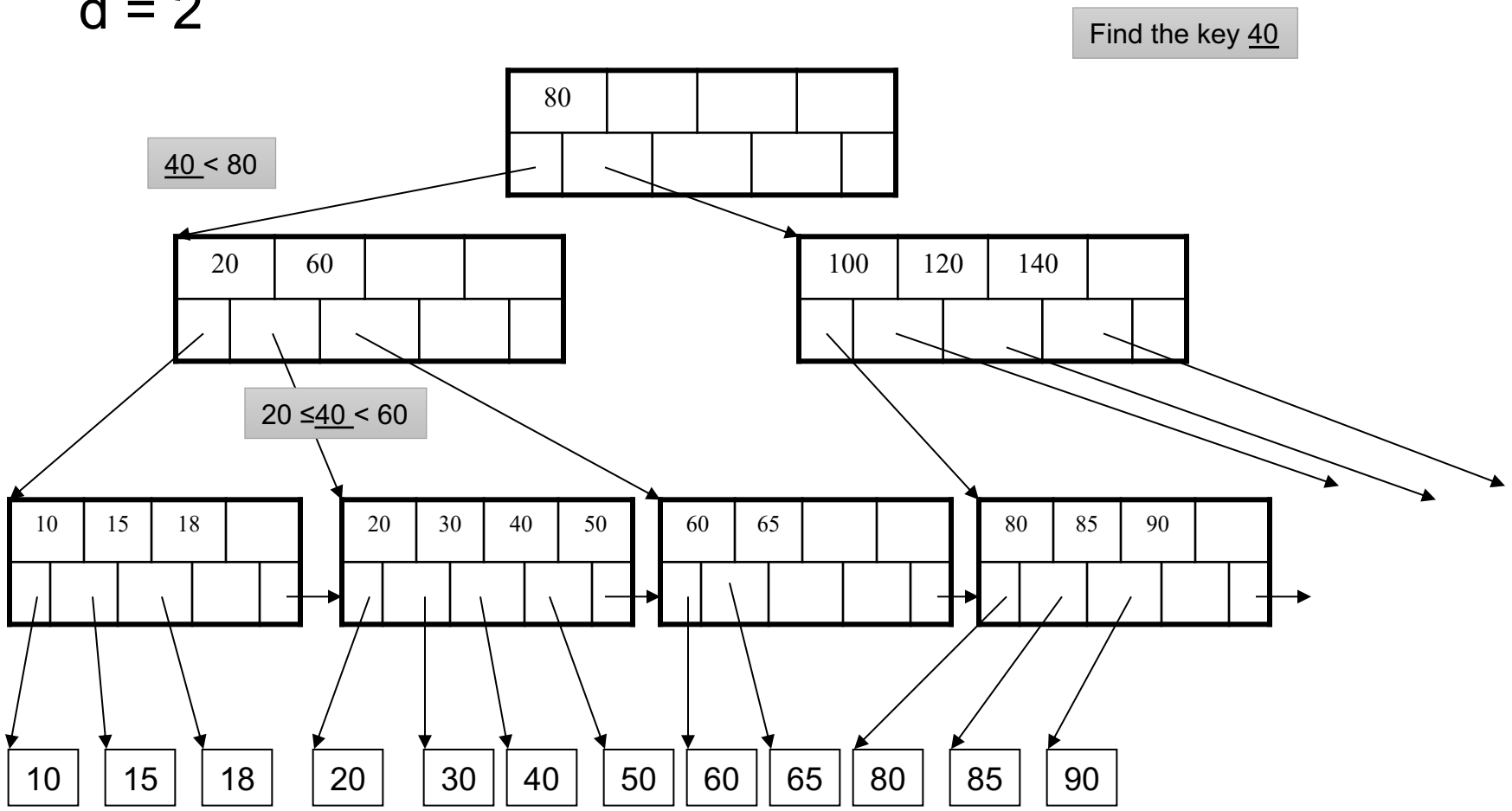
- Search trees

- Idea in B Trees
  - Make 1 node = 1 page (= 1 block)
  - Maximize number of children per node
  - Ideal is to keep height as small as possible

- Idea in B+ Trees
  - Keys are stored on the leaves (not internal nodes)
  - Leaves are linked in a list, for range queries

# B+ Tree Example

d = 2



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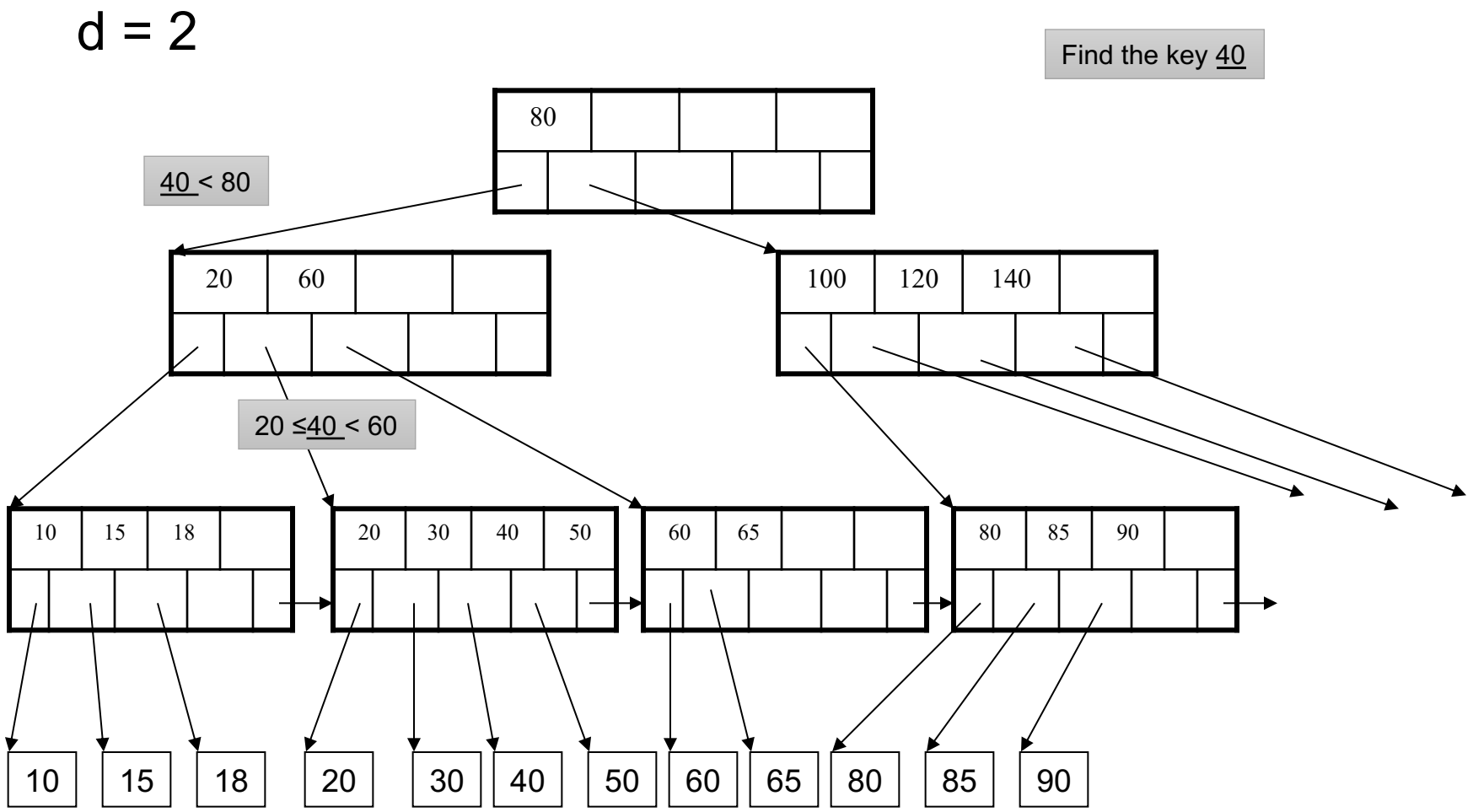

# B+ Trees Properties

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

# B+ Trees Details

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

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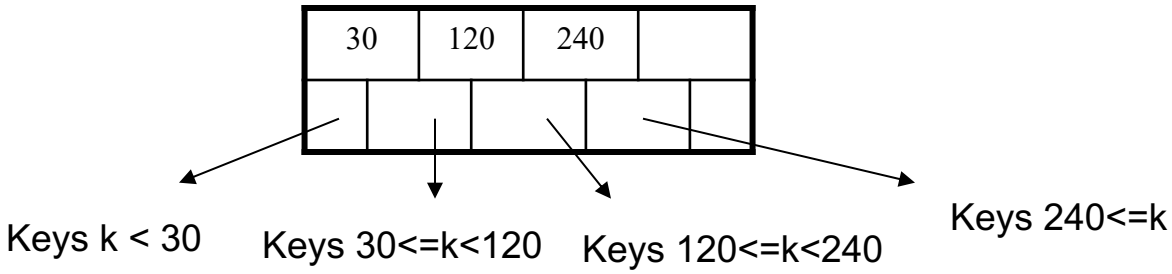

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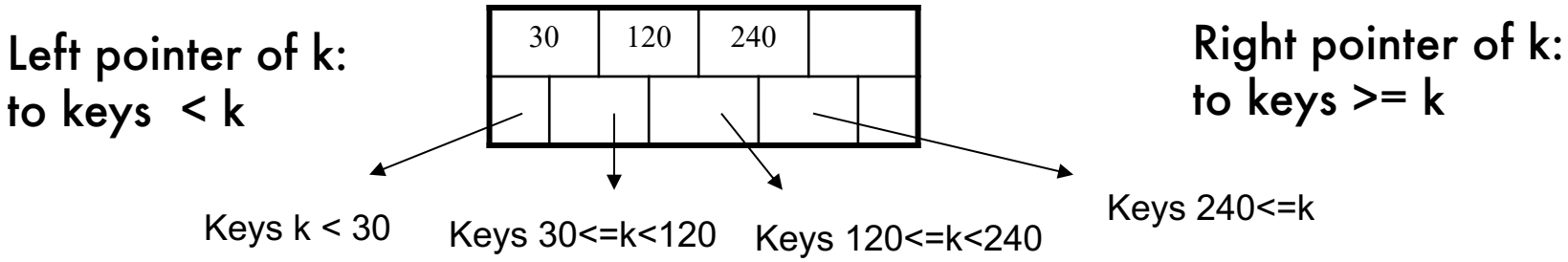

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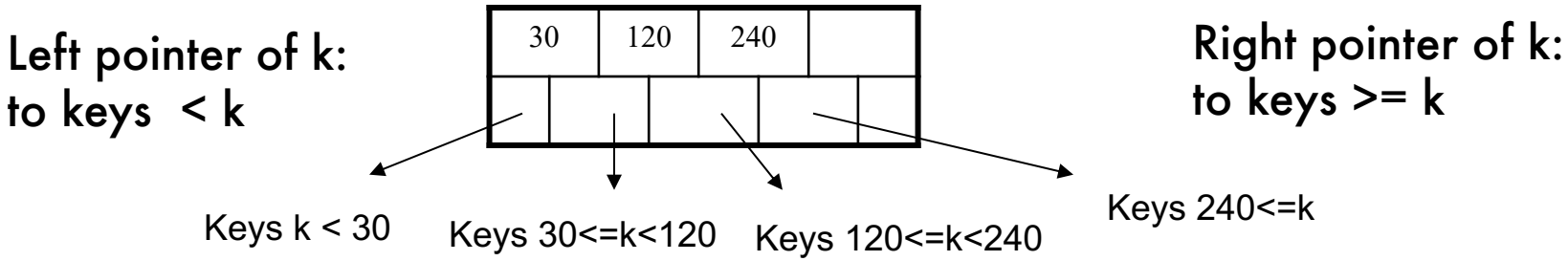
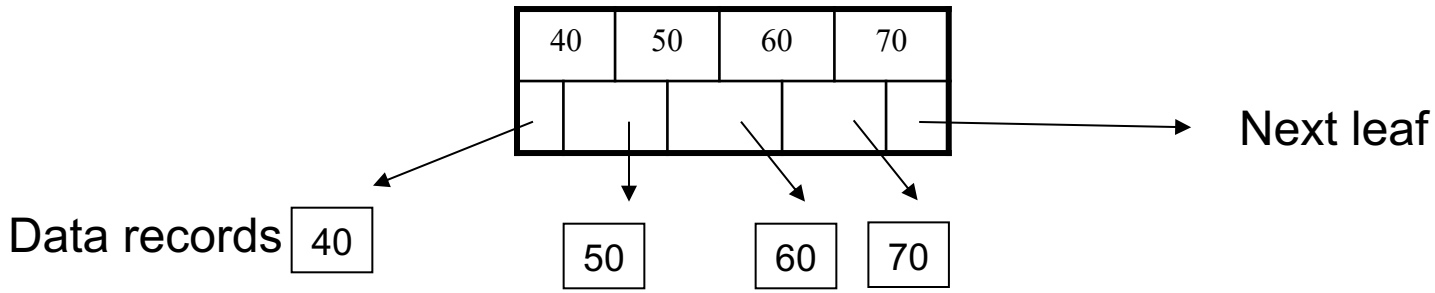
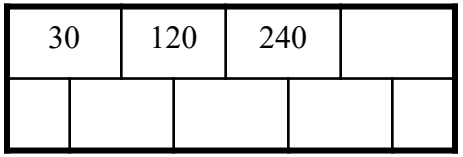



- Each leaf has **d <= m <= 2d keys**:



# 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 x 4 + (2d+1) x 8 <= 4096
- d = 170

# B+ Trees in Practice

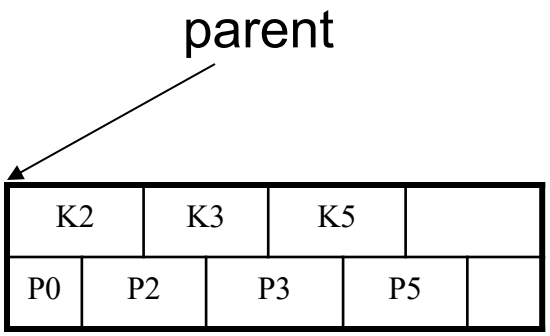
- Typical order: d=100. Typical fill-factor: 66%.
  - average node fanout (children) = 200*0.66 = 133
- Typical capacities
  - Height 4: $133^4$ = 312,900,700 records
  - Height 3: $133^3$ = 2,352,637 records
- Can often hold top levels in buffer pool
  - Level 1 = 1 page = 8 Kbytes
  - Level 2 = 133 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

Insert k1



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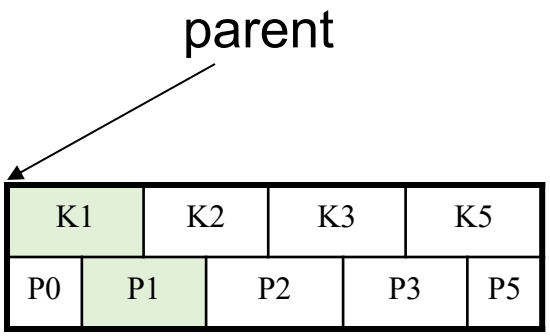

# Insertion in a B+ Tree

Insert (K, P)

- Find leaf where K belongs, insert
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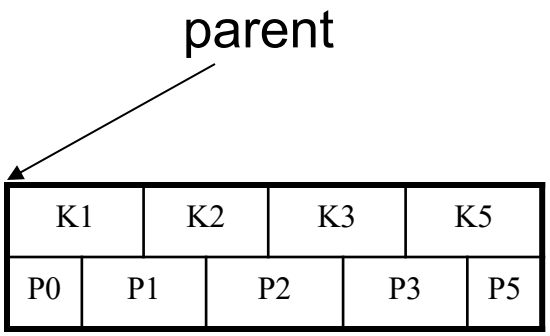
Insert k4



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- Find leaf where K belongs, insert
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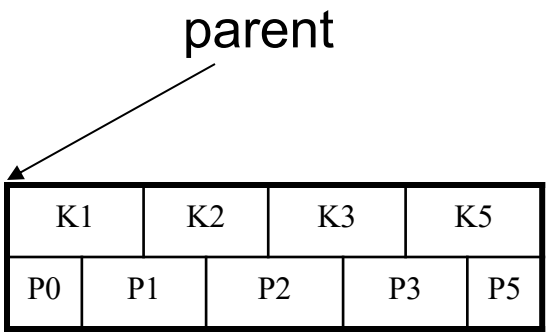
- If overflow (2d+1 keys), split node, insert in parent:

Insert k4



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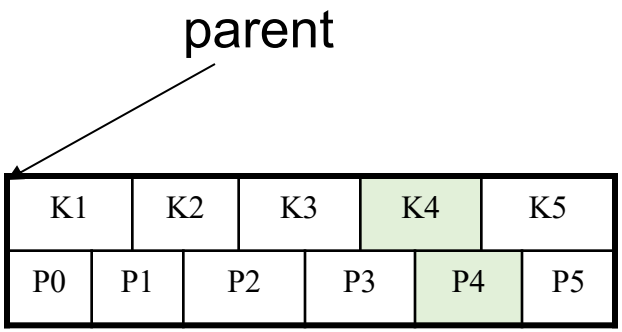

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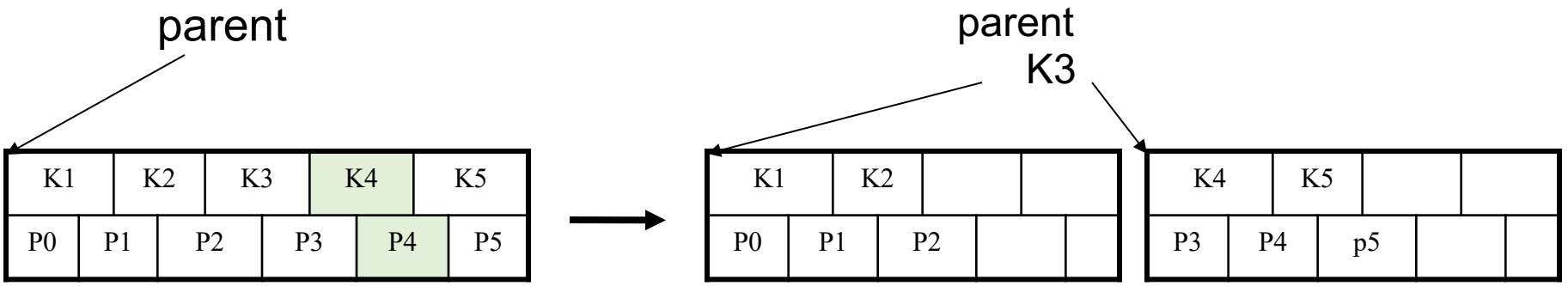

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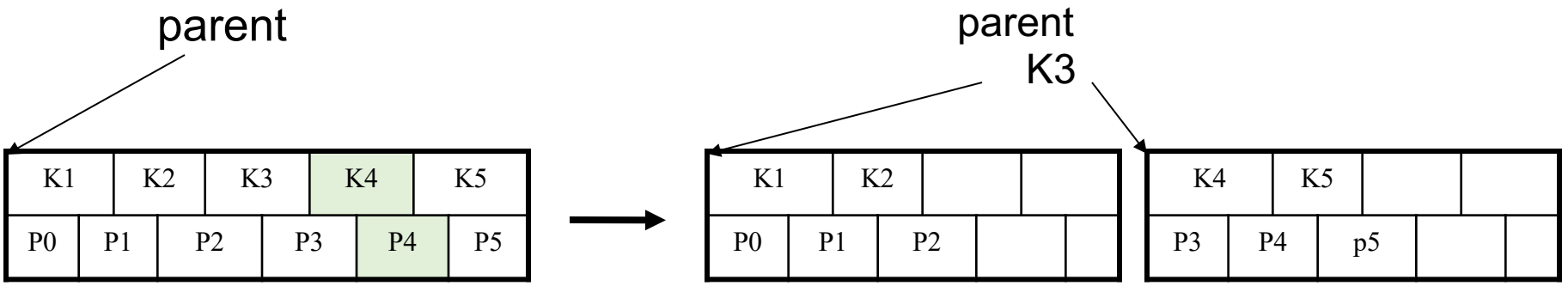
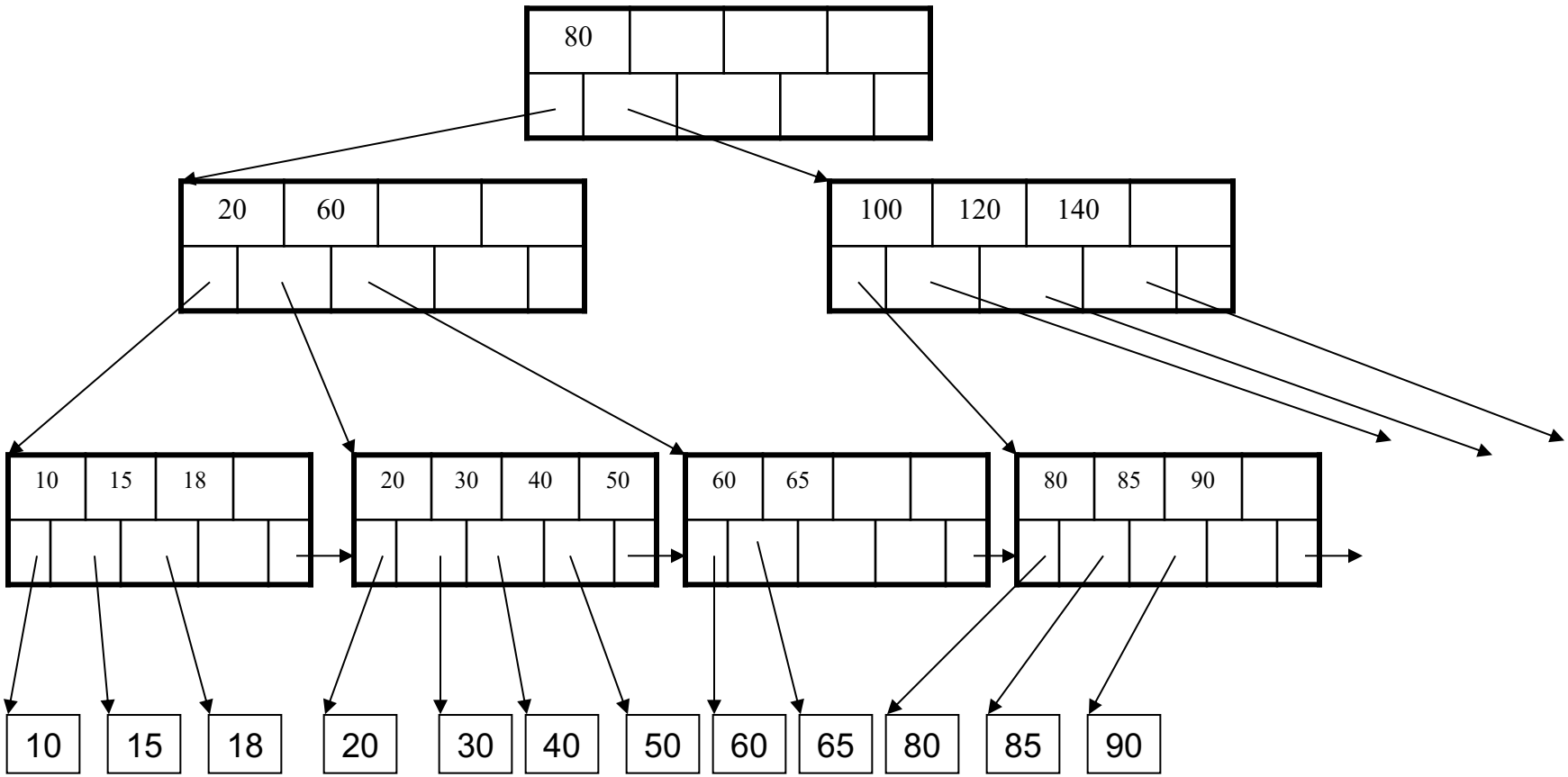



- If leaf, also keep K3 in right node
- When root splits, new root has 1 key only

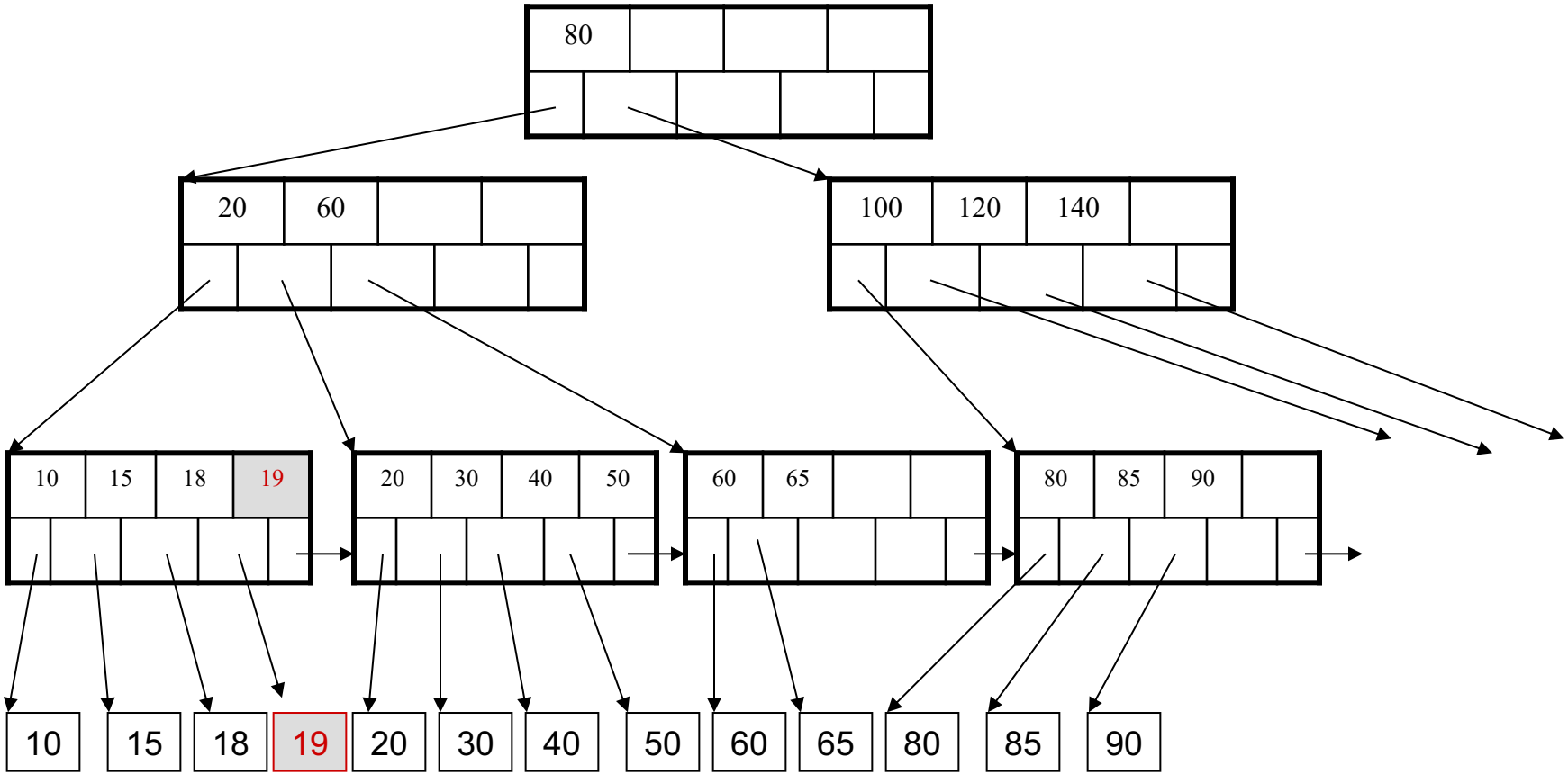
# Insertion in a B+ Tree

Insert K=19



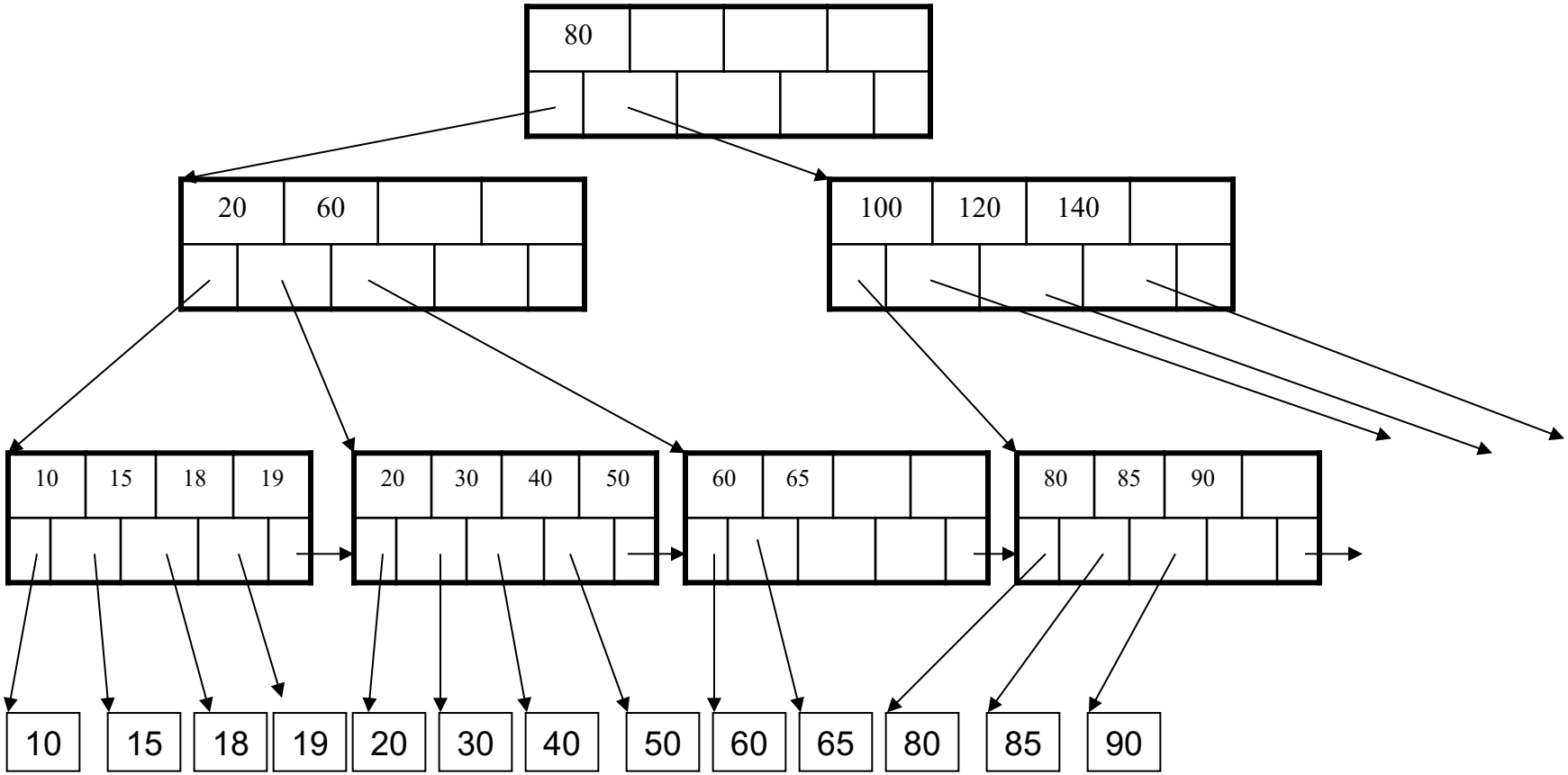
# Insertion in a B+ Tree

After insertion



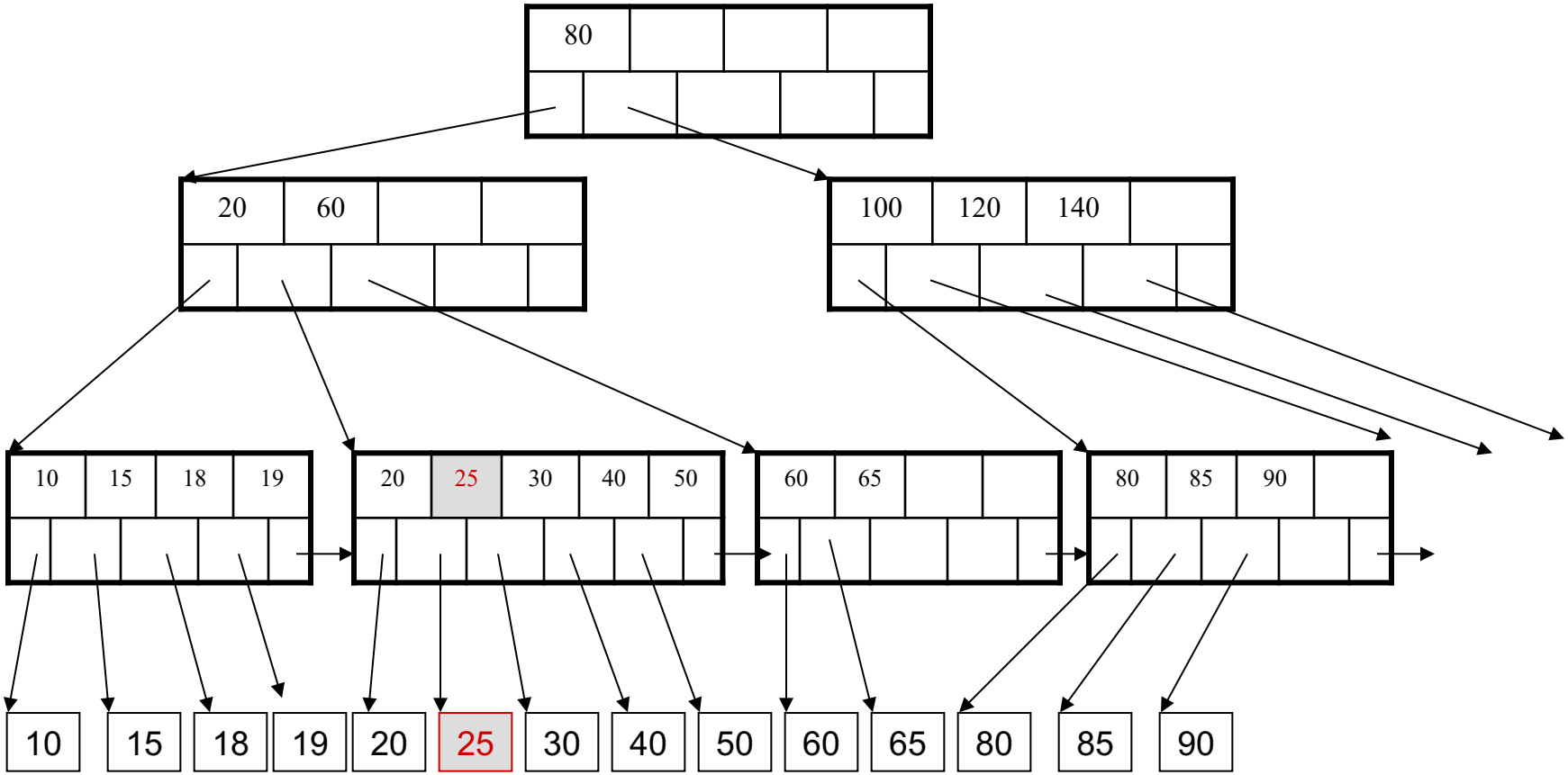
# Insertion in a B+ Tree

Now insert 25



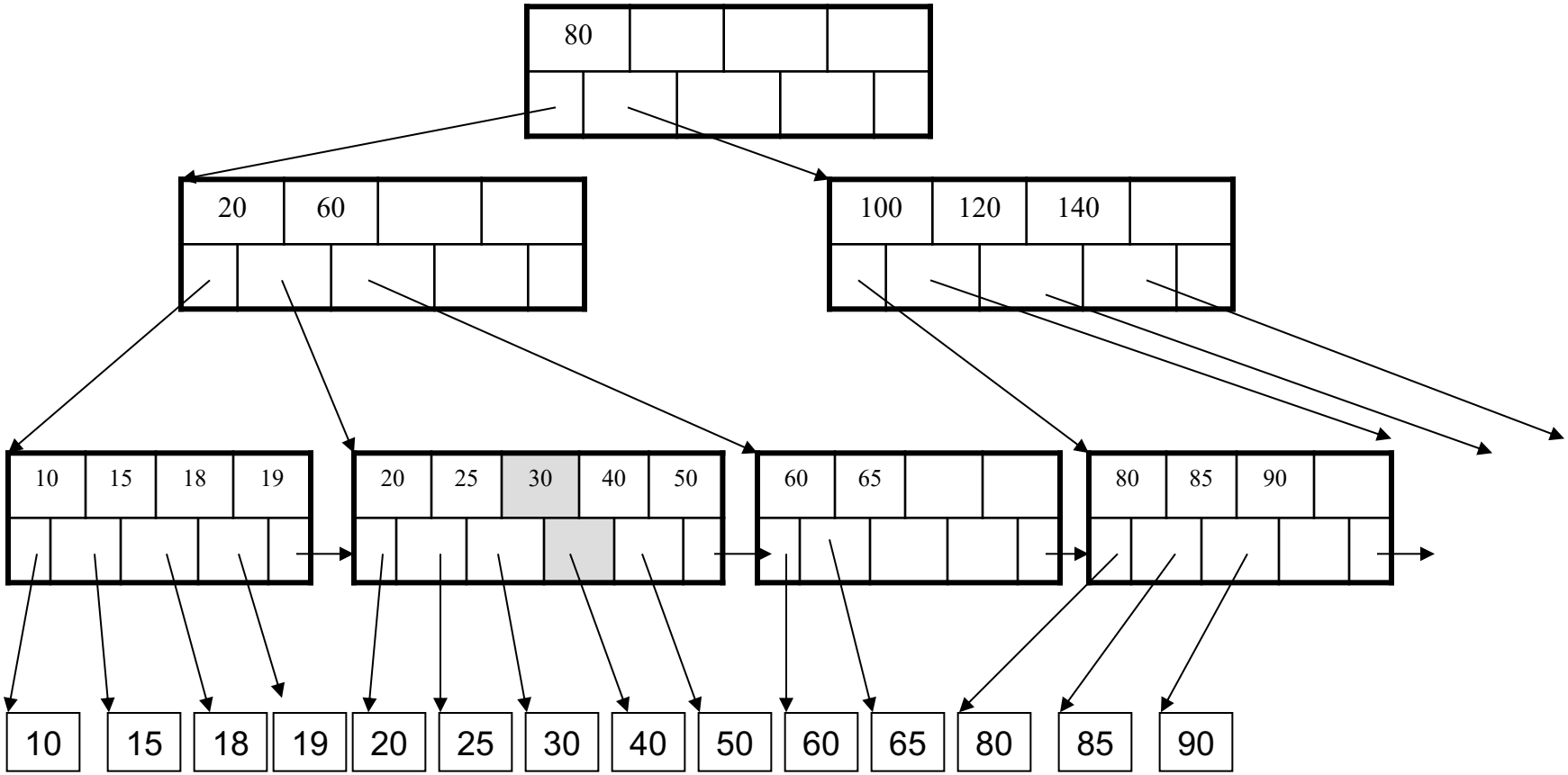
# Insertion in a B+ Tree

After insertion



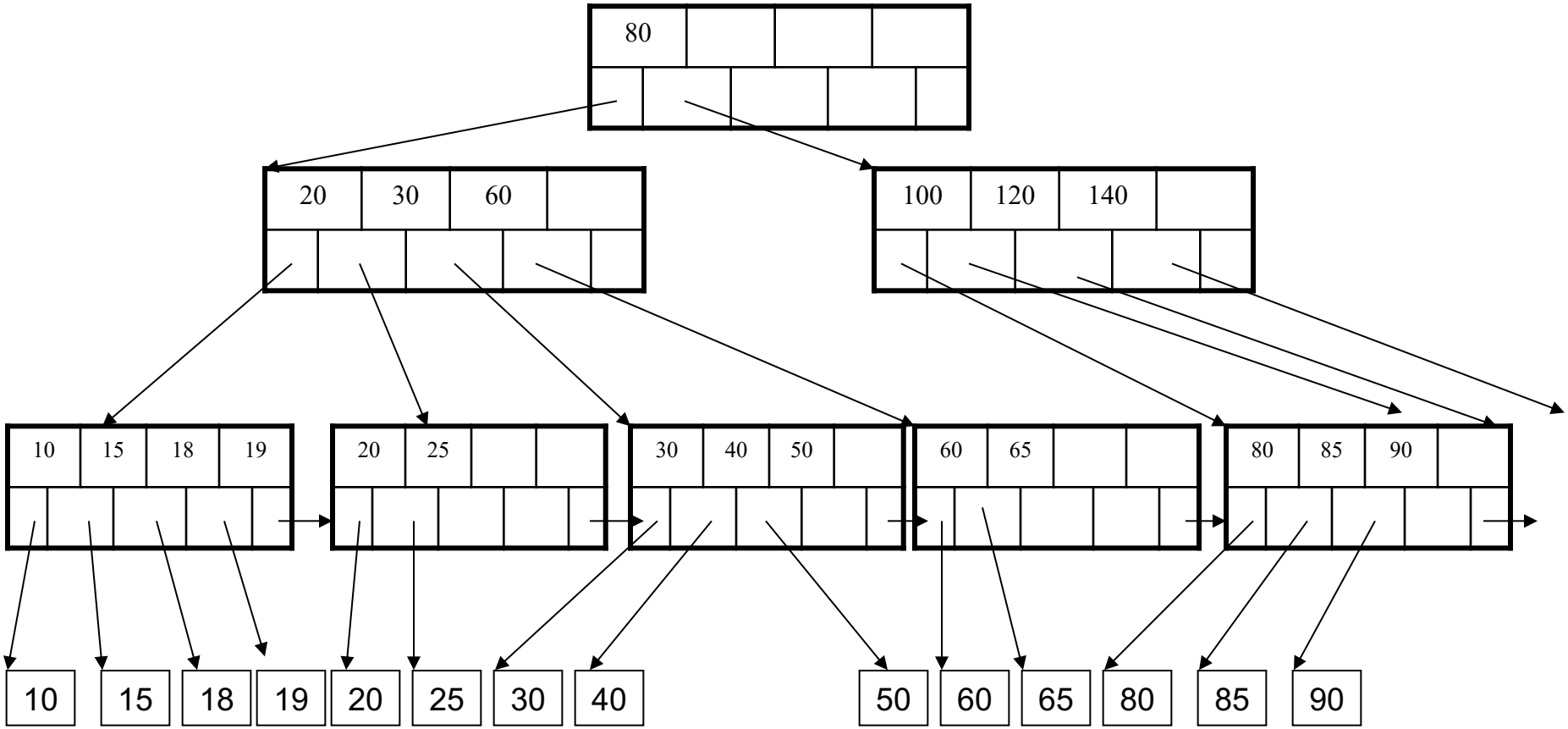
# Insertion in a B+ Tree

But now have to split !



# Insertion in a B+ Tree

After the split



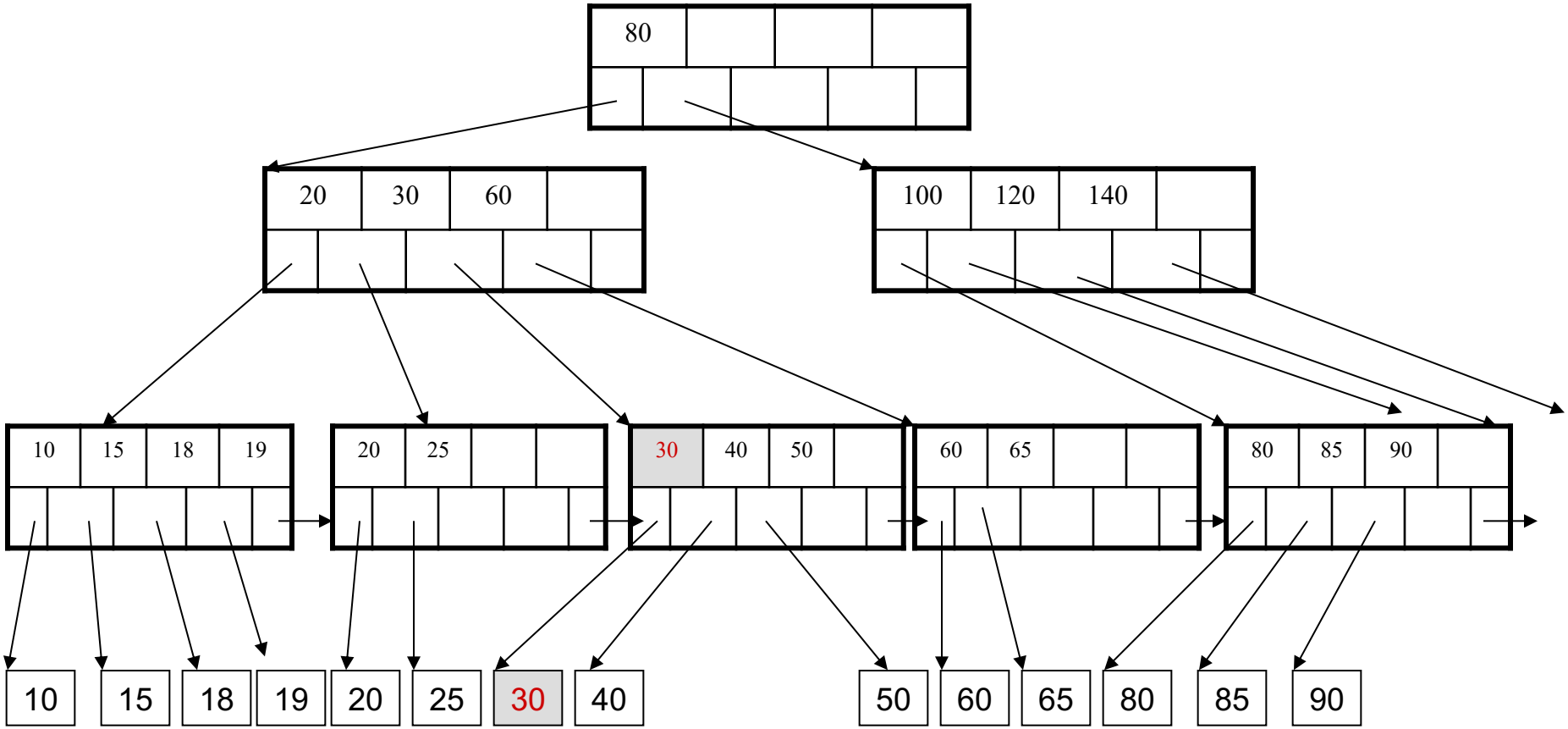
# Deletion in a B+ Tree

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 50% full, merge with on adjacent node
  This removes a key/child from parent;
  repeat algorithm on parent node

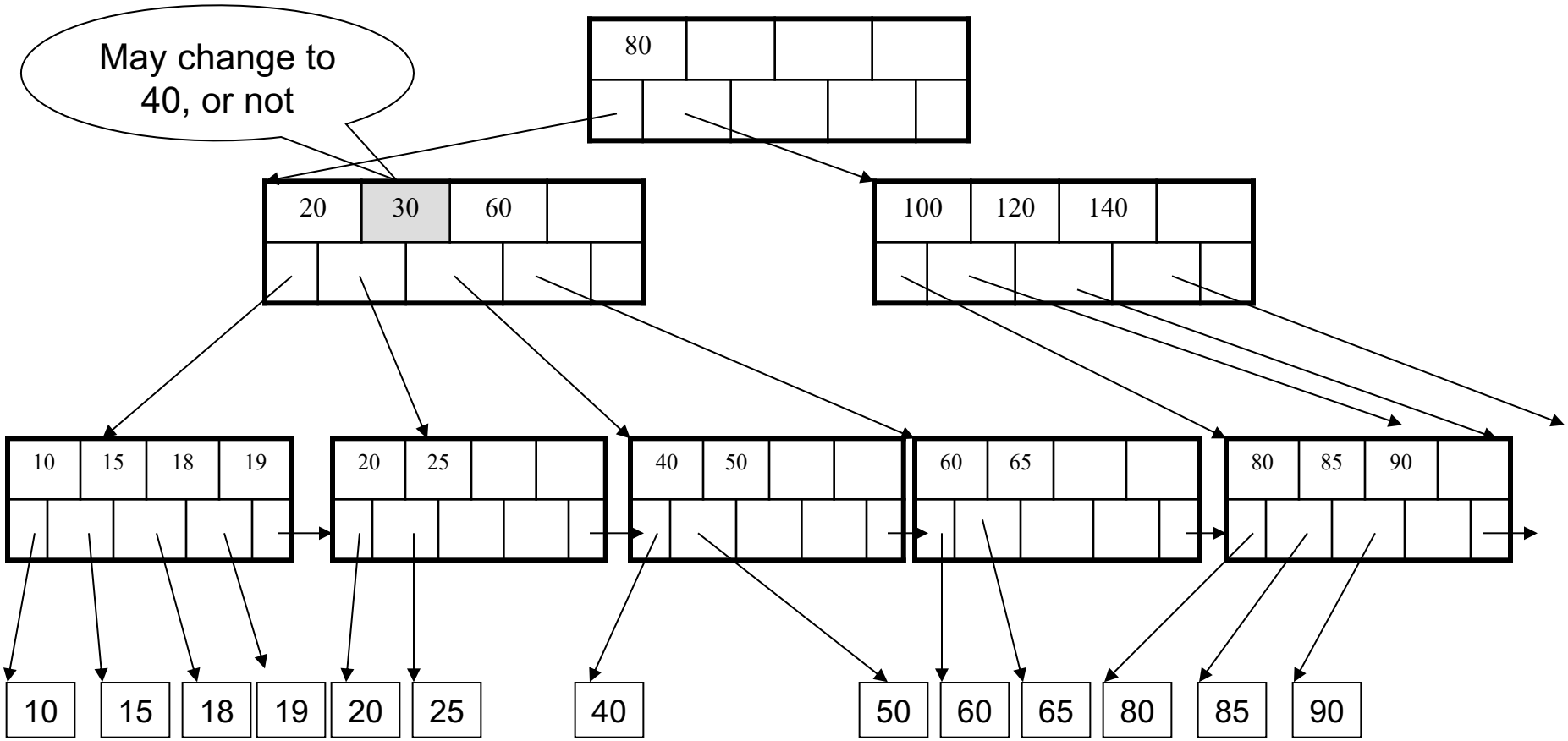
# Deletion from a B+ Tree

Delete 30



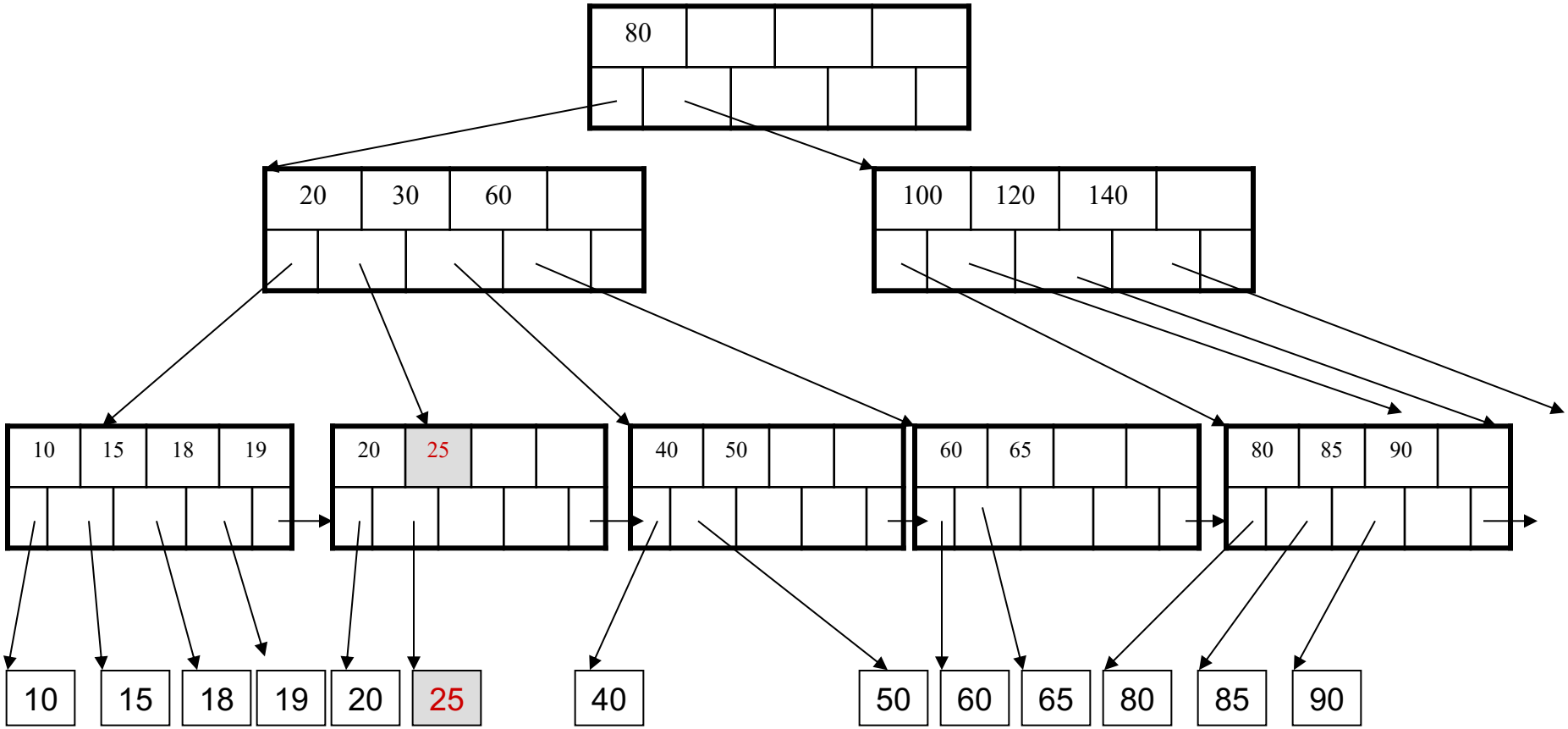
# Deletion from a B+ Tree

After deleting 30



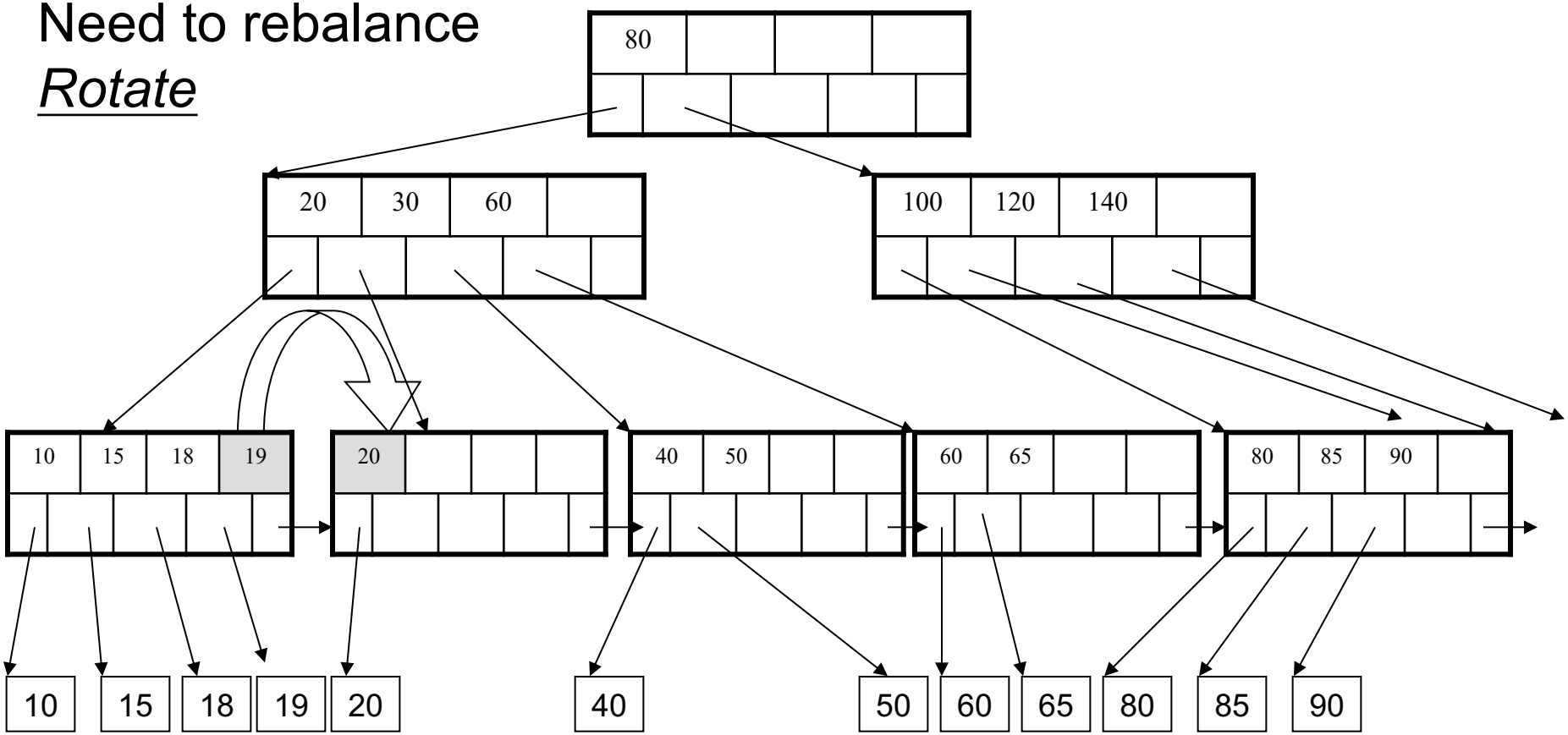
# Deletion from a B+ Tree

Now delete 25



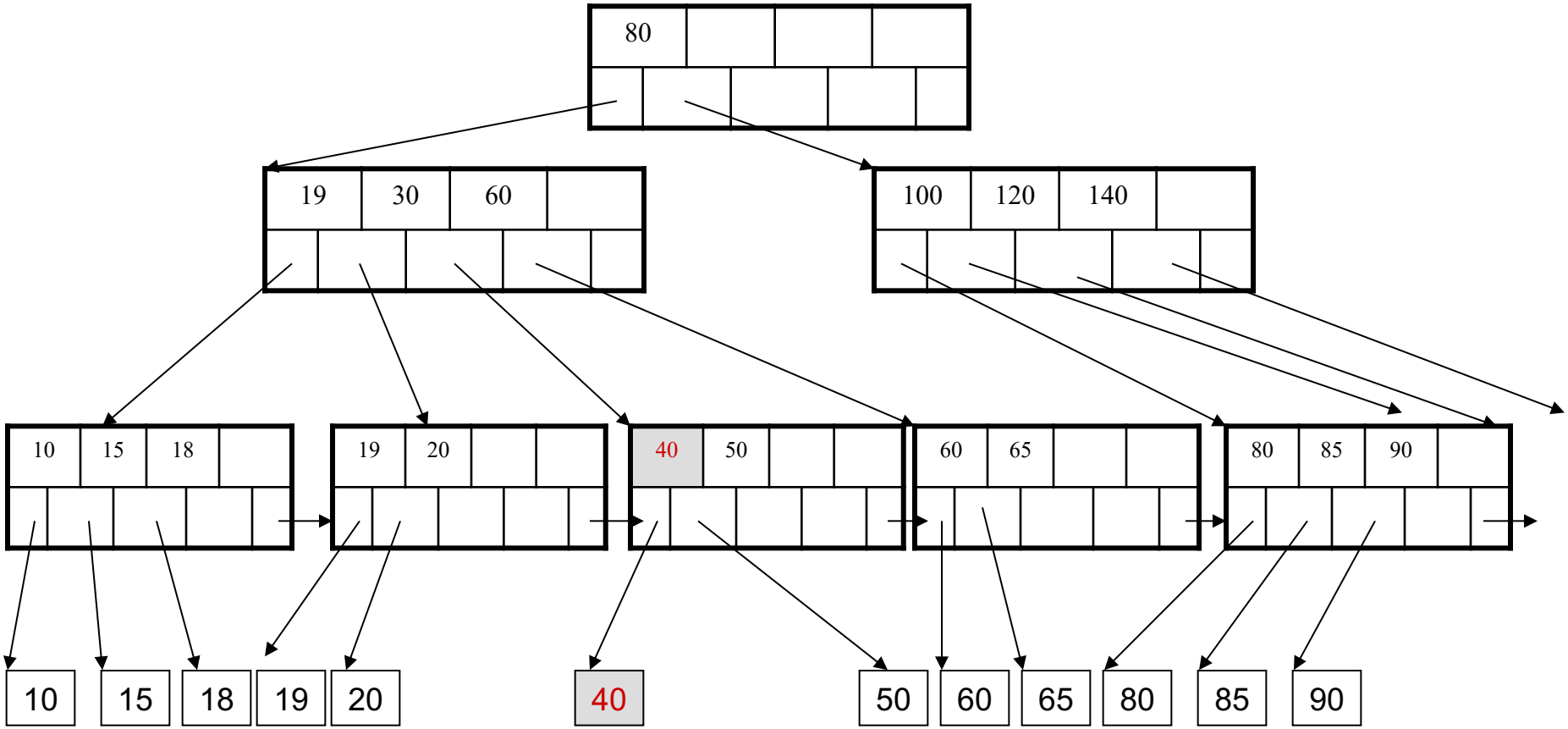
# Deletion from a B+ Tree

After deleting 25
Need to rebalance
*Rotate*



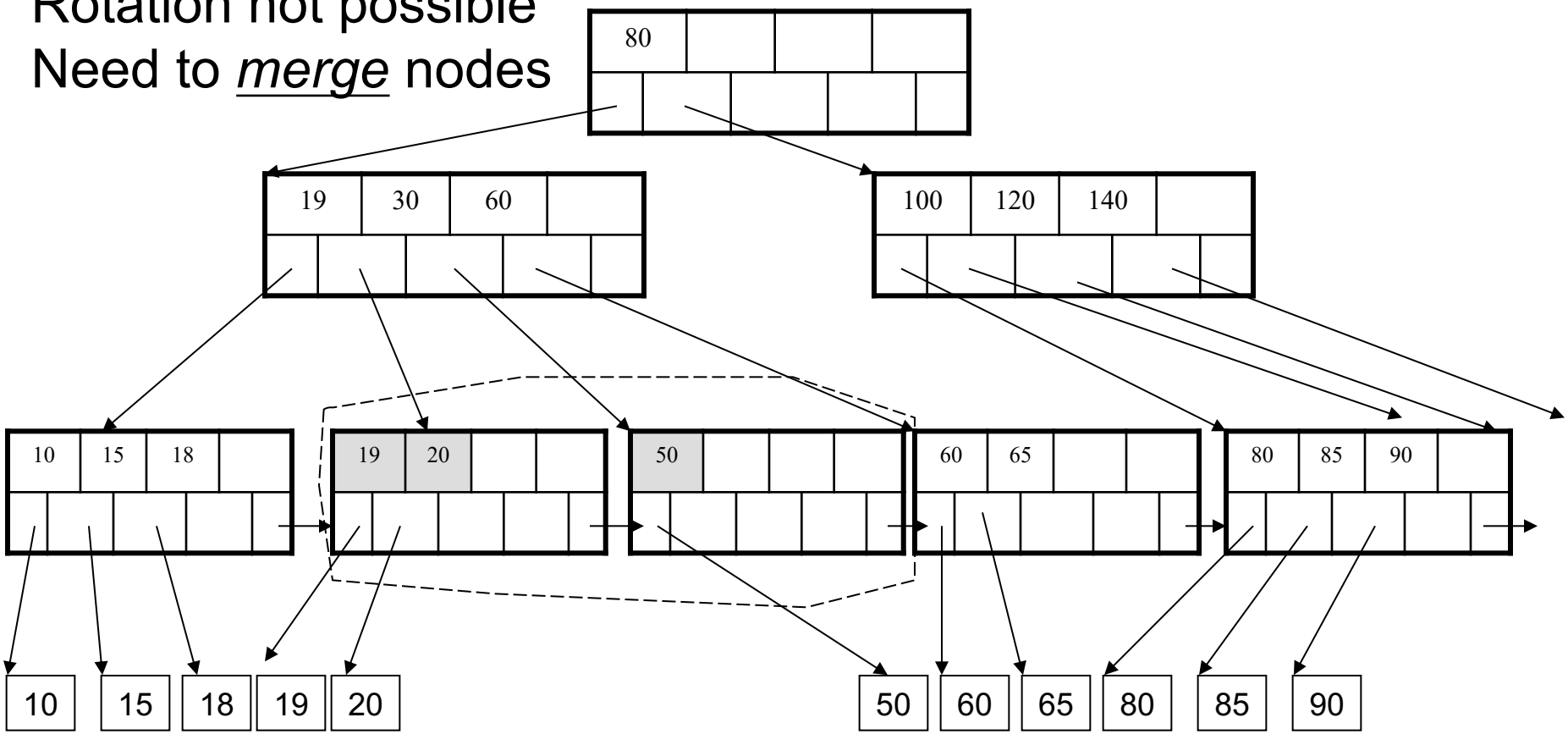
# Deletion from a B+ Tree

Now delete 40



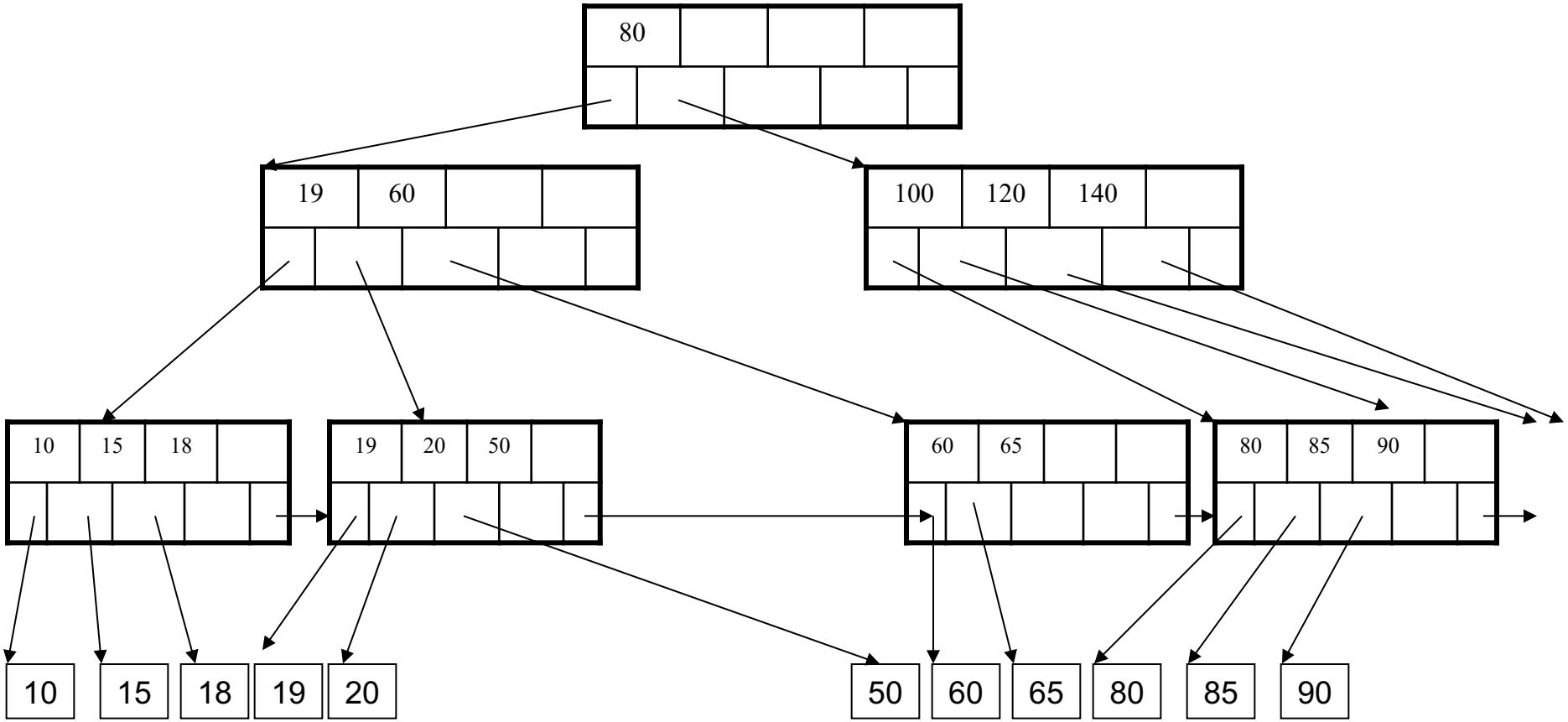
# Deletion from a B+ Tree

After deleting 40
Rotation not possible
Need to *merge* nodes

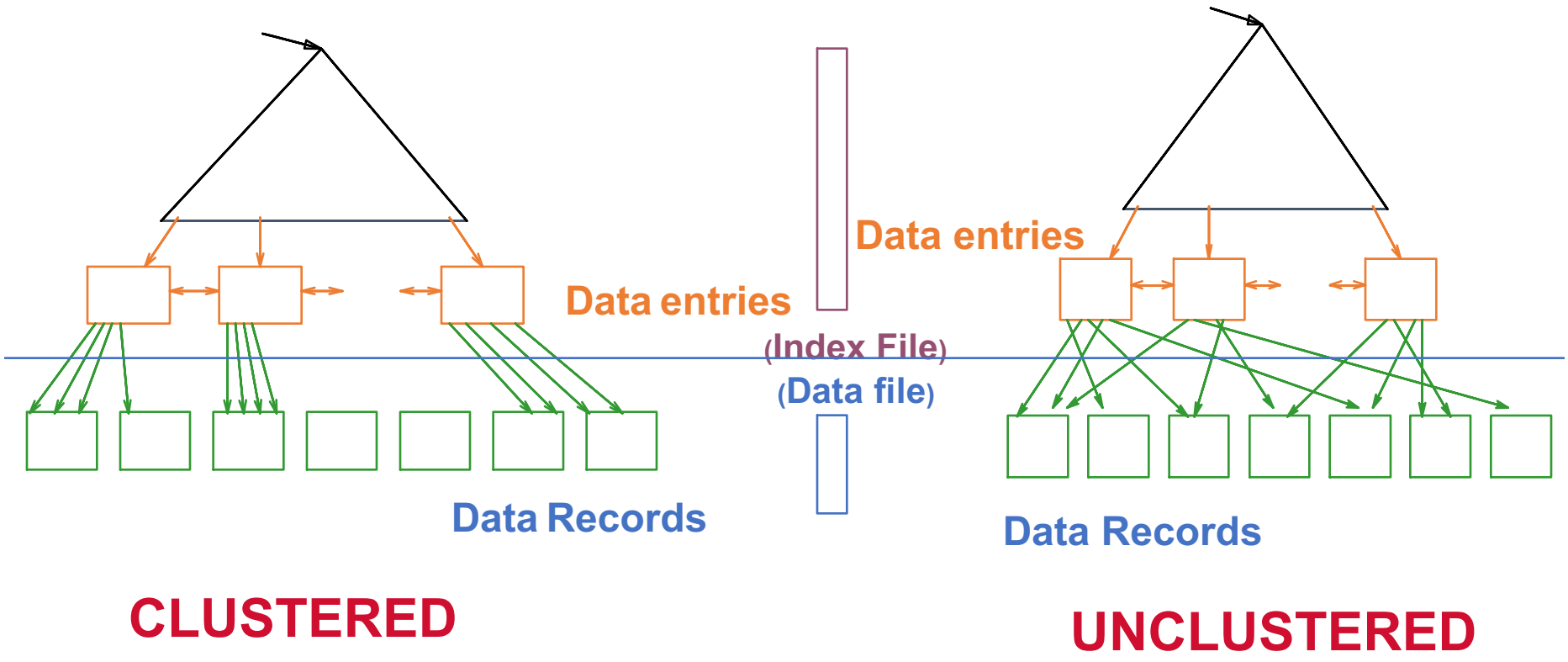


# Deletion from a B+ Tree

Final tree



# Clustered v.s. Unclustered B+ Trees




Note: can also store data records directly as data entries

# 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
```

- Less effective for multi-range
  - Can only use one B+ tree, ignore the other(s)
  - Called *access path selection*

```
Select name
From Student
Where age = 25
    and GPA = 3.5
```

# Summary on B+ Trees

- Default index structure on most DBMSs
- Many improvements/optimizations
  - Prefix compression:
    "Johannes", "John", "Johnson", "Jon",...
    store only suffices, to save space
  - Allow fill capacity to decrease slightly below 50% to avoid cascading splits and merges
  - Optimizations for transactions: tree-locking protocol instead of Strict 2PL
- For multi-dimensional queries, need R-trees:
  - E.g. age = 25 and GPA > 3.5
  - R-trees are more difficult to search and rebalance

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