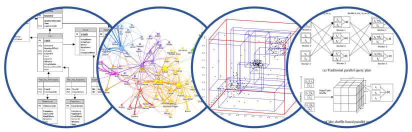

Database System Internals
Indexing

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University of Washington, Seattle

1

Announcements

(still waiting to hear about room)

- Homework 1:
  - New option to submit by Gradescope pdf, or paper copy
  - We will scan your paper copies into gradescope.
  - https://www.gradescope.com/courses/81552
- 544 paper 1 report due week from Friday

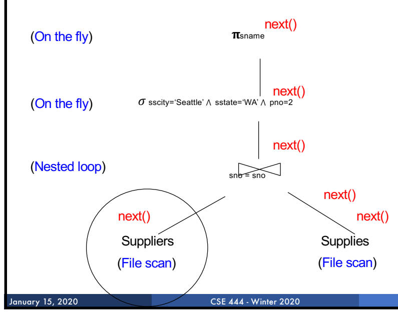
2

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

3

Query Execution How it all Fits



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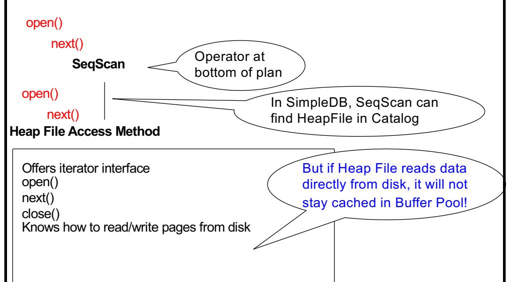
Query Execution In SimpleDB



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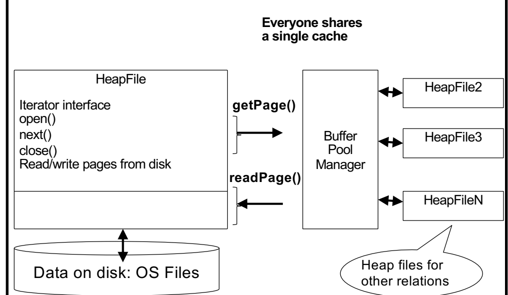
Query Execution In SimpleDB



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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

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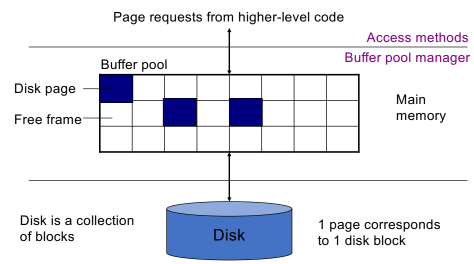
Buffer Manager



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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

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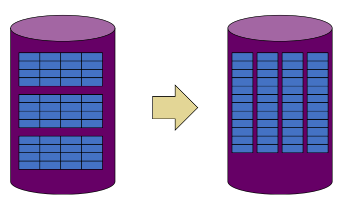
Alternate Design: Column Store



Rows stored contiguously on disk (+ tuple headers)

Columns stored contiguously on disk (no headers needed)

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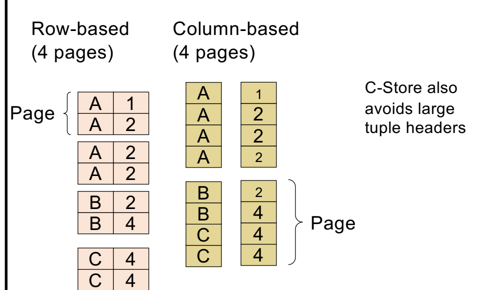
Column Store Illustration



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Conclusion

- Row-store storage managers are most commonly used today for OLTP systems
- They offer high-performance for transactions
- But column-stores win for analytical workloads
- They are widely used in OLAP
  - Microsoft Azure - SQL Data Warehouse
  - Amazon Redshift

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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

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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

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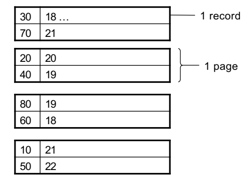
Searching in a Heap File

File is not sorted on any attribute

`Student(sid: int, age: int, …)`



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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?

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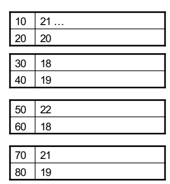
Sequential File

File sorted on an attribute, usually on primary key

`Student(sid: int, age: int, …)`



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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

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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
```


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Outline

- Index structures
- Hash-based indexes

Today

- B+ trees

Next time

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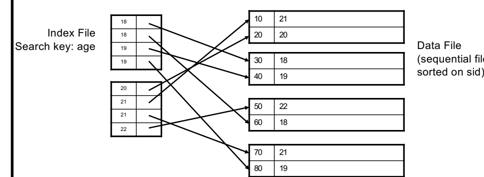
Indexes

- **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 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



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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"

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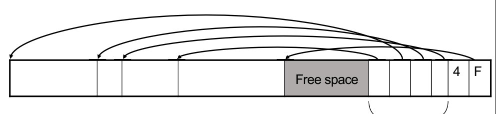
Page Format Approach 2



Header contains slot directory

+ Need to keep track of # of slots

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

Slot directory

Each slot contains <record offset, record length>

Can handle variable-length records

Can move tuples inside a page without changing RIDs

RID is (PageID, SlotID) combination

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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

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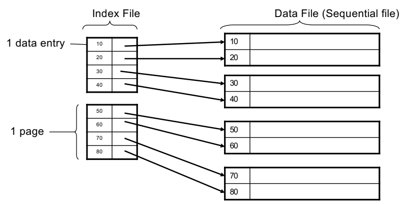
Primary Index

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



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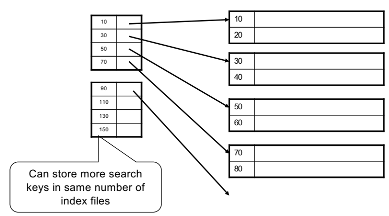
Primary Index

- Sparse index



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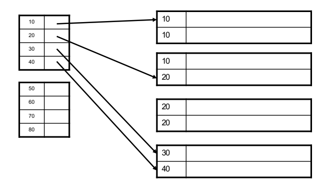
Primary Index with Duplicate Keys

- Dense index:



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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?

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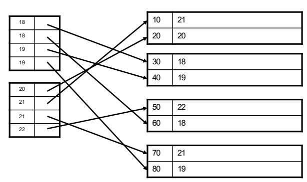
Secondary Indexes

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



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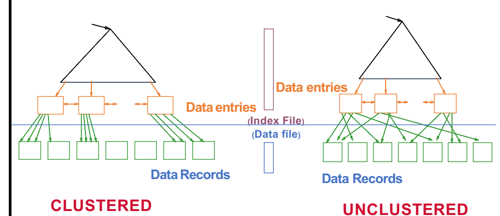
Clustered vs. Unclustered Index



Clustered = records close in index are close in data

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Clustered/Unclustered

- Primary index = clustered by definition
- Secondary indexes = usually unclustered

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Secondary Indexes

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

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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 / …

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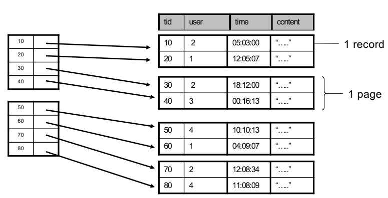
Ex1. Primary Dense Index (tid)



- 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

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Improve from Primary Clustered Index?

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

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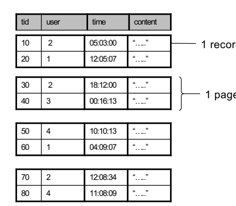
Ex2. Draw a primary sparse index on "tid"



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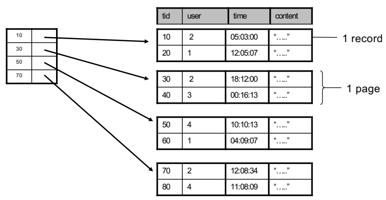
Ex2. Primary Sparse Index (tid)



- Only one index file page instead of two

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Large Indexes

- What if index does not fit in memory?
- Would like to index the index itself
  - Hash-based index
  - Tree-based index

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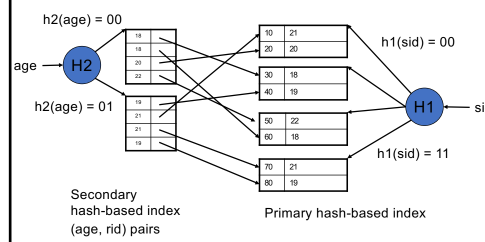
Hash-Based Index

Good for point queries but not range queries



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Tree-Based Index

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

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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

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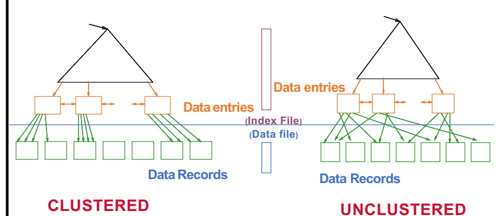

Note: can also store data records directly as data entries

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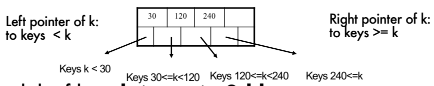
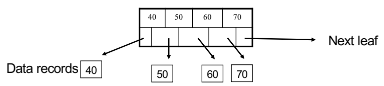
B+ Trees Basics

- 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**:



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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

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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
```


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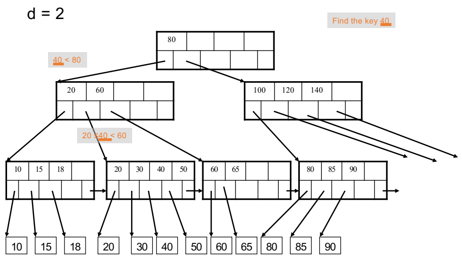
B+ Tree Example

d = 2



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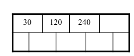
B+ Tree Design

- How large d ?
- Example:
  - Key size = 4 bytes
  - Pointer size = 8 bytes
  - Block size = 4096 bytes
- 2d x 4 + (2d+1) x 8 <= 4096
- d = 170



(e.g. d = 2)

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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

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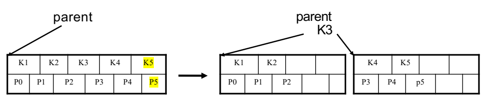
Insertion in a B+ Tree

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

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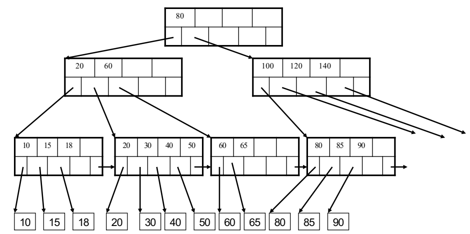
Insertion in a B+ Tree

Insert K=19



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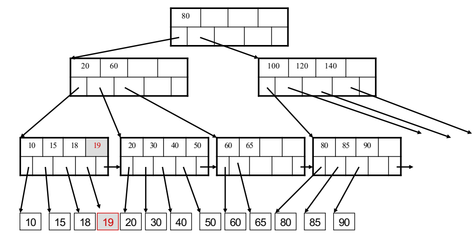
Insertion in a B+ Tree

After insertion



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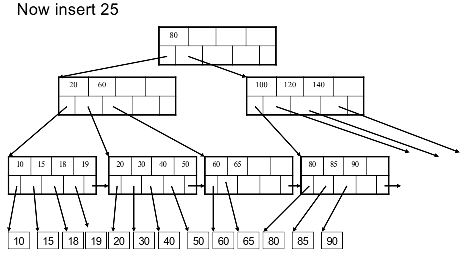
Insertion in a B+ Tree

Now insert 25



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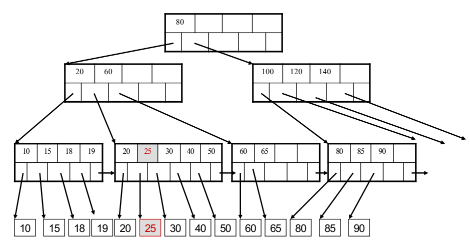
Insertion in a B+ Tree

After insertion



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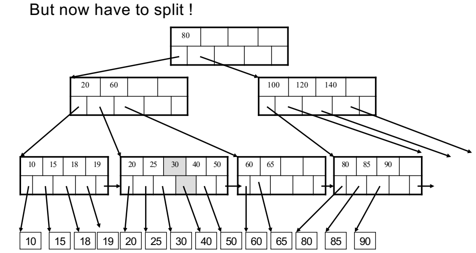
Insertion in a B+ Tree

But now have to split !



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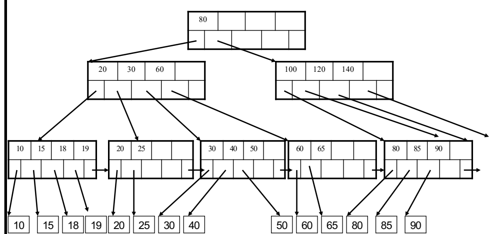
Insertion in a B+ Tree

After the split



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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

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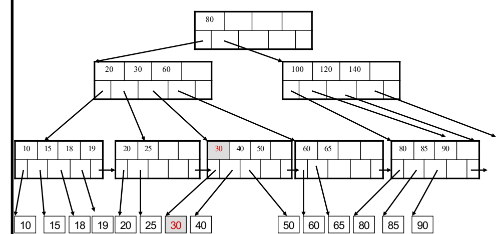
Deletion from a B+ Tree

Delete 30



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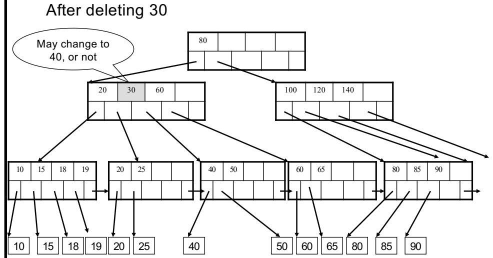
Deletion from a B+ Tree

After deleting 30



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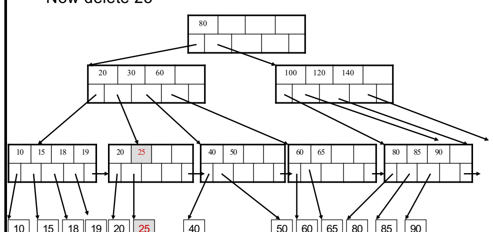
Deletion from a B+ Tree

Now delete 25



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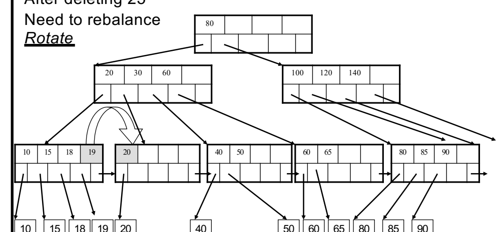
Deletion from a B+ Tree

After deleting 25

Need to rebalance

Rotate



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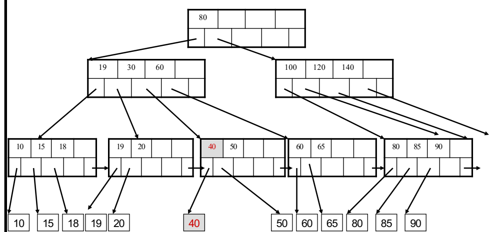
Deletion from a B+ Tree

Now delete 40



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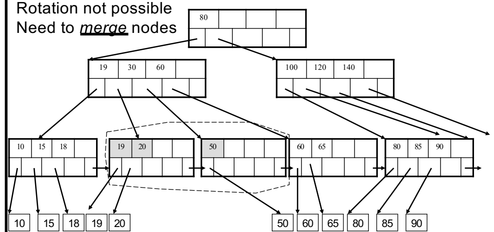
Deletion from a B+ Tree

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



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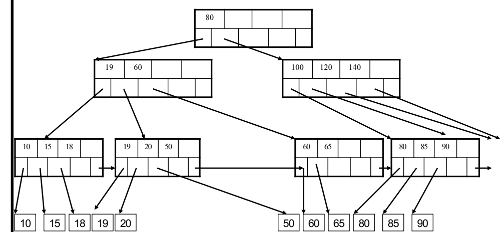
Deletion from a B+ Tree

Final tree



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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

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