Data intensive systems

By Youssef Boughizane

Notes taken for EPFL's CS300 course. There are probably some mistakes and typos. If you find any, please submit a PR to **https://github.com/youssef62/youssef62.github.io** or write me.

- Selection
- Projection
- Joins

Week 11 Relational Query Optimization

Week 12 Transaction Management

Week 13 Concurrency Control I

- Phantom

SQL

The Basics

The main components of an SQL query are :

- `FROM` Compute cross-product of tables (e.g., Students and Enrolled).
- `WHERE` Check for a condition.
- `SELECT` Delete unwanted files.
- `DISTINCT` Iliminate duplicates.

Example 1: All students of age 18.

```
SELECT *
FROM Students S
Where S.age = 18
```

An SQL table like the following is also called a *relation* :

sid	name	login	age	gpa
53666	Jones	jones@cs	18	3.4
53688	Smith	smith@ee	18	3.2

Querying Multiple Relations:

Name and course id of a student and a course where the student got a grade of "B" at this course.

```
SELECT S.name, E.cid
FROM Students S, Enrolled E
WHERE S.sid=E.sid AND E.grade='B'
```

Query evaluation

1. First the cross product is computed : all combinations of a row from first table and a row from second table are computed.
2. WHERE is applied ot filter.

S.sid	S.name	S.login	S.age	S.gpa	E.sid	E.cid	E.grade
53666	Jones	jones@cs	18	3.4	53831	Carnatic101	C
53666	Jones	jones@cs	18	3.4	53832	Reggae203	B
53666	Jones	jones@cs	18	3.4	53650	Topology112	A
53666	Jones	jones@cs	18	3.4	53666	History105	B
53688	Smith	smith@ee	18	3.2	53831	Carnatic101	C
53688	Smith	smith@ee	18	3.2	53831	Reggae203	B
53688	Smith	smith@ee	18	3.2	53650	Topology112	A
53688	Smith	smith@ee	18	3.2	53666	History105	B

Problem: Average `age` of sailors whose `rating` is 10

Solution: Aggregate operators

```
COUNT (*)
COUNT ( [DISTINCT] A)
SUM ( [DISTINCT] A) # add distinct to remove duplicates.
AVG ( [DISTINCT] A)
MAX (A)
MIN (A)
```

Example :

```
SELECT AVG (S.age)
FROM Sailors S
WHERE S.rating=10
```

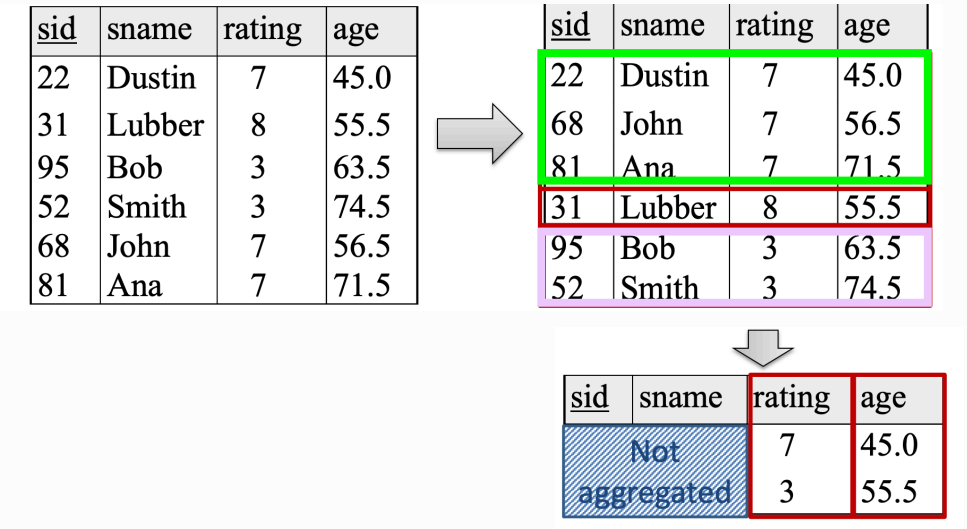
Problem: Find the age of the youngest sailor for each rating level

sid	sname	rating	age
22	Dustin	7	45.0
31	Lubber	8	55.5
95	Bob	3	63.5
52	Smith	3	74.5
68	John	7	56.5
81	Ana	7	71.5

Solution: Group BY - HAVING

```
SELECT MIN (S.age), S.rating
FROM Sailors S
GROUP BY S.rating
HAVING COUNT(*) > 1
```

How is this query evaluated ?



Remark: When we group by an attribute, that attribute must be present in the select clause.

Modifications

Creating a table:

```
CREATE TABLE Enrolled(sid CHAR(20),cid CHAR(20),grade CHAR(2))
```

Adding row:

```
INSERT INTO Students (sid, name, login, age, gpa)
VALUES ('53688', 'Smith', 'smith@cs', 18, 3.2)
```

Deleting rows:

```
DELETE
FROM Students S
WHERE S.name = 'Smith'
```

Nested queries: Names of sailors who have reserved boat #103.

Using `IN` :

```
SELECT S.sname
FROM Sailors S
WHERE S.sid IN (SELECT R.sid
                FROM Reserves R
                WHERE R.bid=103)
```

We can do the same thing using `EXISTS` :

```
SELECT S.sname
FROM Sailors S
WHERE EXISTS (SELECT *
 FROM Reserves R
 WHERE R.bid=103 AND S.sid=R.sid)
```

To find sailors who've not reserved #103 – `NOT IN` or `NOT EXISTS`.

Expressions

We can do arithmetic in `SELECT` :

```
SELECT S.age, S.age-5 AS age1, 2*S.age AS age2
FROM Sailors S
WHERE S.sname = 'dustin'
```

Also possible in `WHERE` :

```
SELECT S1.sname AS name1, S2.sname AS name2
FROM Sailors S1, Sailors S2
WHERE 2*S1.rating = S2.rating - 1
```

Strings:

`%` stands for 0 or more arbitrary characters. `_` stands for any one character. So for example "one" satisfies `o_e`.

```
SELECT S.age, age1=S.age-5, 2*S.age AS age2
FROM Sailors S
WHERE S.sname LIKE 'B_%b'
```

More operatiosn:

- `UNION` : sailors who reserved red or green boat.
- `INTERSECT` : sailors who reserved red **and** green boats.

  More useful than `UNION`.

  E.g: without `INTERSECT` :

  ```
  SELECT R1.sid
  FROM Boats B1, Reserves R1,
   Boats B2, Reserves R2
  WHERE R1.sid=R2.sid
   AND R1.bid=B1.bid
   AND R2.bid=B2.bid
   AND (B1.color='red' AND B2.color='green')
  ```

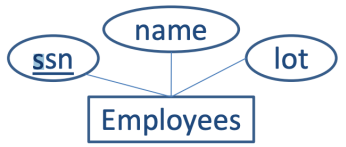
With :

```
SELECT S.sid
FROM Sailors S, Boats B,
Reserves R
WHERE S.sid=R.sid AND R.bid=B.bid AND B.color=‘red’

INTERSECT

SELECT S.sid FROM Sailors S, Boats B,
Reserves R
WHERE S.sid=R.sid AND R.bid=B.bid AND B.color=‘green’
```

- `EXCEPT` : Set difference.
- `ANY` : Find sailors whose rating is greater than that of some sailor called Horatio.

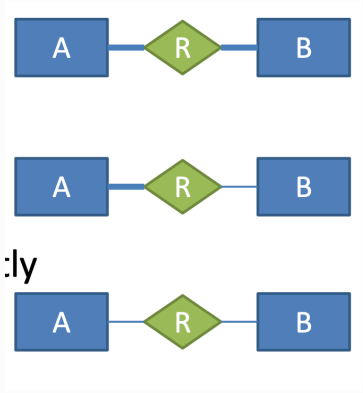
```
SELECT *
FROM Sailors S
WHERE S.rating > ANY (SELECT S2.rating
                      FROM Sailors S2
                      WHERE S2.sname=‘Horatio’)
```

ER to SQL conversion




```
CREATE TABLE Employees (
 ssn CHAR(11), # CHAR( #nb of characters )
 name CHAR(30),
 lot INTEGER,
 PRIMARY KEY (ssn) # specify the primary key
);
```

Many to many relations

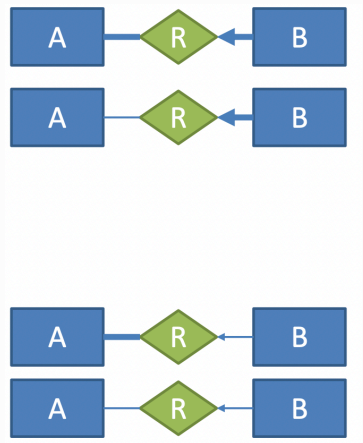


- These 3 cases are dealt with similarly. In fact, we don't enforce the atleast constraint.
- Primary key is (pk(A),pk(B)). (because one a can be in relation with many b and vice versa)

Example:

```
CREATE TABLE Works_In(
 ssn CHAR(11),
 did INTEGER,
 since DATE,
 PRIMARY KEY (ssn, did),
 FOREIGN KEY (ssn) REFERENCES Employees,
 FOREIGN KEY (did) REFERENCES Department
);
```

One to many relations



Two possibilites :

1. Create a table for R, with only B as primary key.
2. Merge R and B: attribute of B + attribute of R + primary key of A.

   ✅ if total participation, we can enforce this by ensuring A NON NULL.

Method (2) has the risk of having much more NULL cells, while (1) creates a new table => trade-off.

example method 2 :

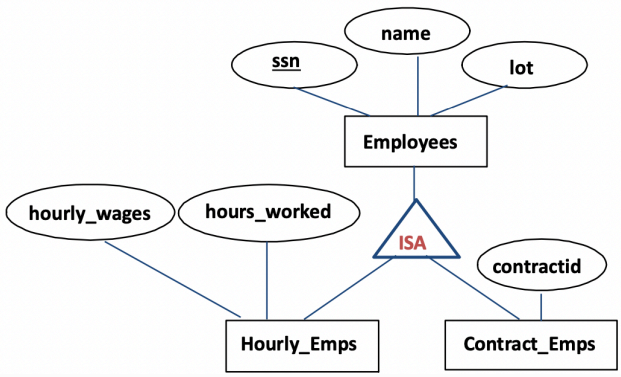
```
CREATE TABLE Dept_Mgr(#Employees: ssn, name, lot | Department did, dname, budget
 did INTEGER,
 dname CHAR(20),
 budget REAL,
 since DATE,
 ssn CHAR(11) NOT NULL,
 PRIMARY KEY (did),
 FOREIGN KEY (ssn) REFERENCES Employees
);
```

One to one constraints:

Merge A and B in one table and set pk of b as pk and set pk of a as UNIQUE. (so an a can map to exactly one b)

Merge B and R in one table, set pk of a as forein key and NON NULL.

Hierarchies

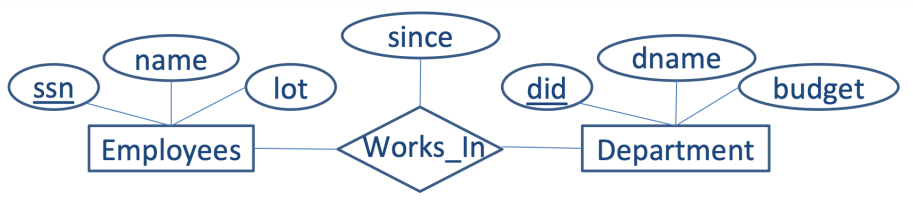



```
CREATE TABLE Hourly_Emps (
   ssn CHAR(11),
   hours_worked REAL,
   hourly_wages REAL,
   PRIMARY KEY (ssn),
   FOREIGN KEY (ssn) REFERENCES Employees
    ON DELETE CASCADE
);
```

Week1 : ER model

Database design layers

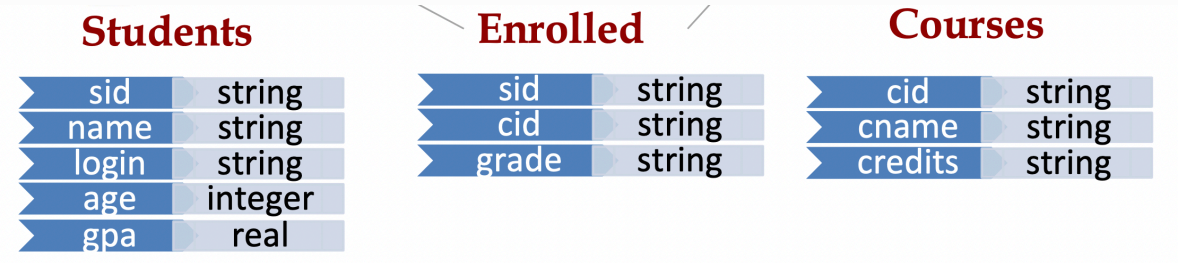
1. **Conceptual design:** High level description (often done with ER model)



2. **Logical design:** Translate ER into DBMS data model (like the relational model)

   relational data model = **Relation** (Table with rows and columns) + **Schema:** columns of a relation

   Schema:

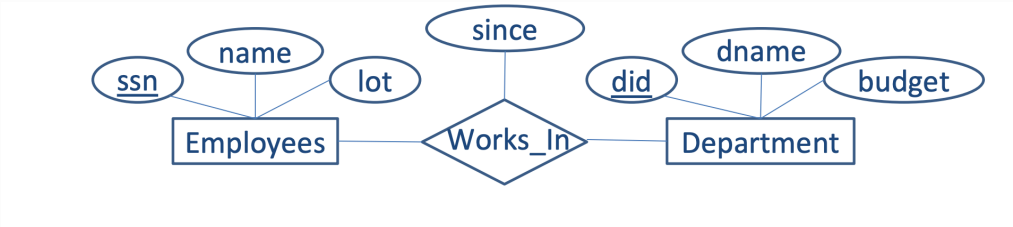


3. other layers to be seen later : Disk layout...

Entity-Relation(ER) model

Entity: a subject like student, courses, employee...

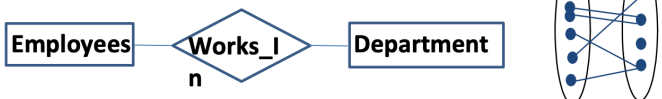
Relationship: Association among two or more entities.



Arrow or not arrow :

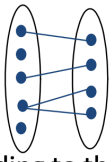
A --> B means that A has a relationship with at most a B.

Key constraints



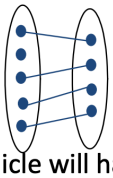
Many-to-Many

An employer can work in **many** departments; a department can have **many** employees



One-to-Many

Each department has **at most one** manager, according to the **key constraint** on Manages



One-to-One

Each driver can drive **at most** vehicle and each vehicle will have **at most one** driver

Thick or not Thick :

A **----** B (as opposed to A---B) means that A is in relation with at least a B.

1. Total participation : each entity needs to participate in a relationship

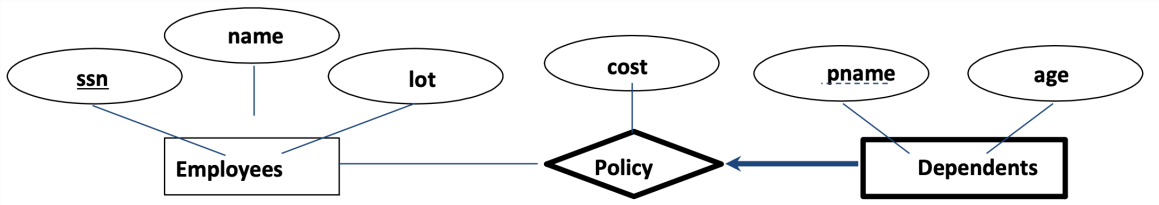
Total Participation

2. Each department has one employee. Each employee can manage at at most one department.

3. Partial partitipation

Partial Participation

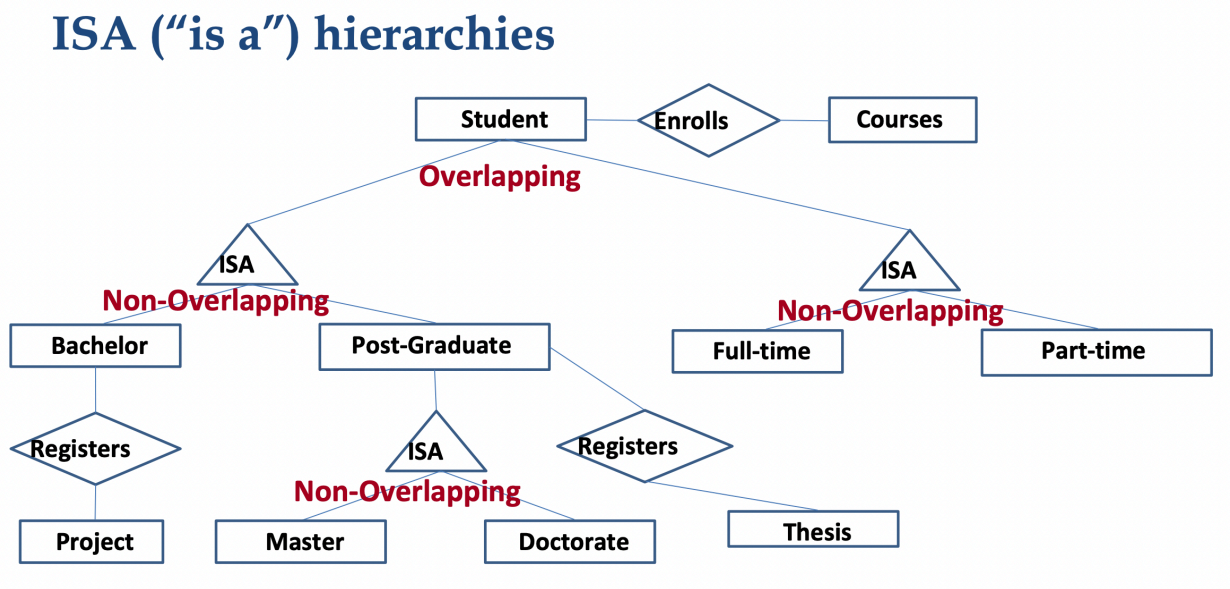
Weak entities



An entity whose existence depends on its relationship with another entity.

An employee can or not have an insurance *policy* (relation) for a closed one (a *Dependent*). A dependent (in our model) only exists if there is an employee has has them if their policy.

ISA relation

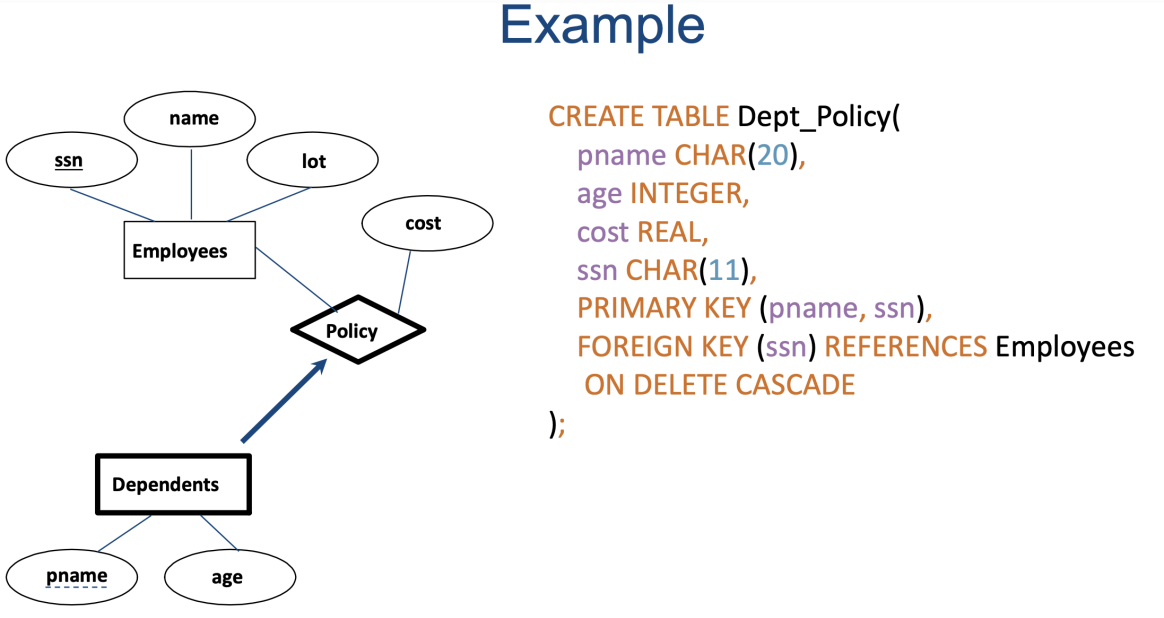


An isa relation can be **overlapping** or **non-overlapping**.

Weak entity

To identify weak entry : we need pk of owner + pk weak entity.

Merge R with the weak entity – Primary key is the combination of the owner entity pk and the weak key.



Week 2: Relational data model

After completing our conceptual design using the ER model, we need to model the data so we can then store it and query it. Many data models exist: relational, object oriented data model, network data model...

We focus on the **relational data** model for its simplicity.

- **Relation(table):** set of named attributes(colums)
- **Tuple(row):** a value for each attribute.
- Each attribute has a type(domain).

It is important to seperate two concepts, the schema(design) and the instance(actual content)

- **Schema**: structural description of relations in database
  - Students(*sid*: string, *name*: string, *login*: string, *age*: integer, *gpa*: real)
- **Instance**: actual contents at a given point in time
  - Cardinality: # rows
  - Arity or degree: # attributes

Students

sid	name	login	age	gpa
50000	Dave	dave@cs	19	3.3
53666	Jones	jones@cs	18	3.4
53688	Smith	smit@ee	18	3.2
...	...	...	...	...

Colleges

name	location	strength
MIT	USA	10000
Oxford	UK	22000
EPFL	CH	9000
...	...	...

We can have special value for “unknown” or “undefined” : `NULL`.

Question: If we query for GPA > 3. 3 and have NULL for some user. If not do we get it in GPA>=3.3 ? (We should get it in one for union consistency)

Students

sid	name	login	age	gpa
50000	Dave	dave@cs	19	3.3
53666	Jones	jones@cs	18	3.4
53688	Smith	smit@ee	18	NULL
...	...	...	...	...

SuperKey: attribute unique to each tuple(row). It also can be a set of attributes that are unique. (e.g colleges below)

Colleges

name	location	strength
MIT	USA	10000
Oxford	UK	22000
EPFL	CH	9000
...	...	...

Key: A superkey that is minimal.

Suppose we chose name,location and strenght to be our superkey, it is indeed a superkey but not a key(not minimal).

Candidate key: If there are multiple possible keys each of them is referred to as a candidate key.

Primary Key: A key chosen by *us*.

Foreign keys: Set of fields in one relation that is used to `refer' to a tuple in another relation.

Students

sid	name	login	age	gpa
50000	Dave	dave@cs	19	3.3
53666	Jones	jones@cs	18	3.4
53688	Smith	smit@ee	18	3.2
...	...	...	...	...

Enrolled

cid	sid	grade
Carnatic101	53666	C
Raggae203	50000	B
Topology112	53666	A
...	...	...

Integrity constraints(IC):

Def condition that must be true for any instance of the database; e.g., domain constraints

- ICs are specified when schema is defined
- ICs are checked when relations are modified

⚠️ **Careful about integrity constraints**

- E.g., "For a given student and course, there is a single grade."

```
CREATE TABLE Enrolled
  (sid CHAR(20)
   cid  CHAR(20),
   grade CHAR(2),
   PRIMARY KEY (sid,cid))
```

VS.

```
CREATE TABLE Enrolled
  (sid CHAR(20)
   cid  CHAR(20),
   grade CHAR(2),
   PRIMARY KEY (sid),
   UNIQUE (cid, grade))
```

The right side code makes a student only able to have one course.

Relational algebra

Five basic operations:

- **Selection** (σ): Selects a subset of rows from relation (horizontal).

S2

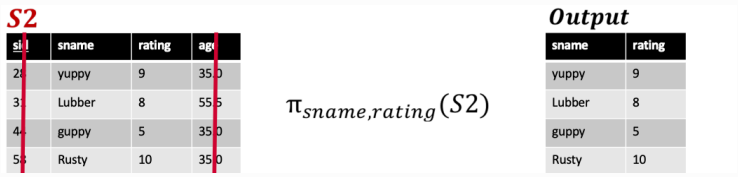
sid	sname	rating	age
~~28~~	~~yuppy~~	~~9~~	~~35.0~~
31	Lubber	8	55.5
44	guppy	5	35.0
~~58~~	~~Rusty~~	~~10~~	~~35.0~~

$\sigma_{rating<9}(S2)$

Output

sid	sname	rating	age
31	Lubber	8	55.5
44	guppy	5	35.0

- **Project** (π): Retains only wanted columns from relation (vertical).



⚠️ Selection(σ) choses rows. SELECT in SQL is to select colums, it refers to Project (π) in relational algebra.

- **Set-difference** (–): Tuples in r1, but not in r2.
- **Union**($\cup$): Tuples in r1 and/or in r2.
- **Cross-product**($\times$): Allows us to combine two relations. Each row of s1 with each row of s2.
- **Rename**(ρ): Renames the list of attributes specified in the form of oldname → newname or position → newname. Renane is usefull to get a coherent cross product.

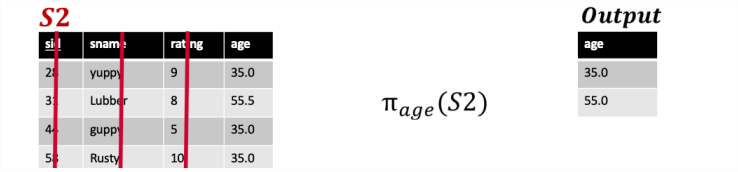
$$\rho_{bname \to boatname,\, color \to boatcolor}(Boats)$$

bid	boatname	boatcolor
101	Interlake	blue
102	Interlake	red
103	Clipper	green
104	Marine	red

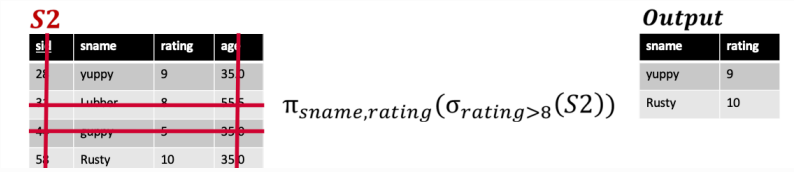
$$\rho_{2 \to boatname,\, 3 \to boatcolor}(Boats)$$

Remark:

These operations output sets:



Composition



in SQL it would be `SELECT sname,rating FROM S2 WHERE rating > 8`.

More relations (compositions of basic relations):

- (natural)**Join** ⋈: compute RXS, select rows where attributes(usually key) have same values, project. $\pi(\sigma(R \times S))$

$\pi_{S1.sid,sname,\ldots}(\sigma_{S1.sid=R1.sid}(\boldsymbol{S1}\times\boldsymbol{R1}))$

sid	sname	rating	age	sid	bid	day
22	Dustin	7	45.0	22	101	10/10/96
22	Dustin	7	45.0	58	103	11/12/96
31	Lubber	8	55.5	22	101	10/10/96
31	Lubber	8	55.5	58	103	11/12/96
58	Rusty	10	35.0	22	101	10/10/96
58	Rusty	10	35.0	58	103	11/12/96

$\boldsymbol{S1} \bowtie \boldsymbol{R1}$

sid	sname	rating	age	bid	day
22	Dustin	7	45.0	101	10/10/96
58	Rusty	10	35.0	103	11/12/96

- **Condition join** $\bowtie_c$

$\boldsymbol{S1}$

sid	sname	rating	age
22	Dustin	7	45.0
31	Lubber	8	55.5
58	Rusty	10	35.0

$\boldsymbol{R1}$

sid	bid	day
22	101	10/10/96
58	103	11/12/96

$\boldsymbol{S1} \bowtie_{S1.sid<R1.sid} \boldsymbol{R1}$

sid	sname	rating	age	sid	bid	day
22	Dustin	7	45.0	58	103	11/12/96
31	Lubber	8	55.5	58	103	11/12/96

- **Division /:** Find all sailors who have reserved **all** boats.

  In A/B, attributes of B are subset of attributes of A. A/B are the "entities" (colums that are in A and not in B) that are in a relationship with all elements of B. (this is not an accurate description).

  E.g : a table A with attributes student_id, course_id and a table B containing courses. A/B would give the students who took all the courses.

sno	pno
s1	p1
s1	p2
s1	p3
s1	p4
s2	p1
s2	p2
s3	p2
s4	p2
s4	p4

A

pno
p2
p4

$B2$

sno
s1
s4

$A/B2$

Remark: Equivalent formulas can express the same output and some are more efficient. (e.g second one below)

$$\pi_{sname}\,(\sigma_{bid=103}\ (Sailors \bowtie Reserves))$$

$$\pi_{sname}\,(Sailors \bowtie (\sigma_{bid=103}\ (Reserves))$$

Boats

bid	bname	color
101	Interlake	blue
102	Interlake	red
103	Clipper	green
104	Marine	red

Sailors

sid	sname	rating	age
22	Dustin	7	45.0
31	Lubber	8	55.5
58	Rusty	10	35.0

Reserves

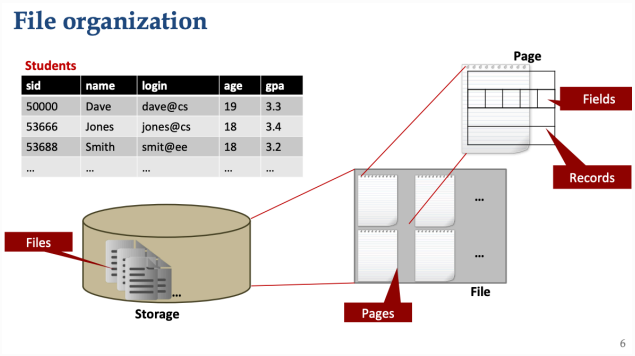
sid	bid	day
22	101	10/10/96
58	103	11/12/96

Week3: Storage, Files, and Indexing

We will answer the following questions:

- **File Organization:** How to organize data in files ?
- **Indexing:** How to make data access efficient ?
- **Storage:** How is data physically stored on disk ?

Each **file** consists of a set of **pages**. Each **page** consists of **fields** and **records**.

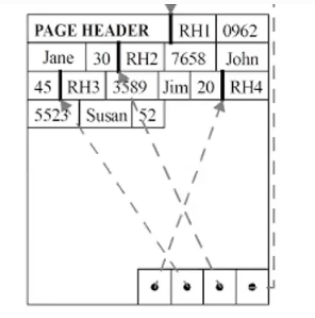


File organization

Page format

How to store data in pages ?

N-ary storage model(NSM): Row by row storage



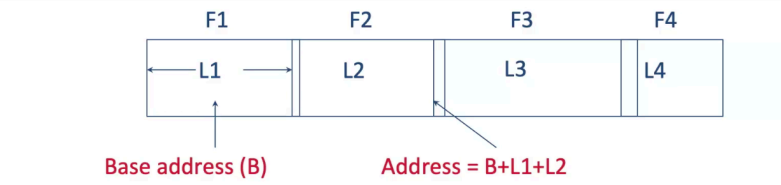
Each pointer points to one record, so we can access specific records fast.

- Each **slot** stores a record.

- PageHeader has information on how much free space in the header. It also has the pointers (unlike the above figure).
- RecordHeader (RH) has information on records. For example for variable size attributes(where they start and where they end)

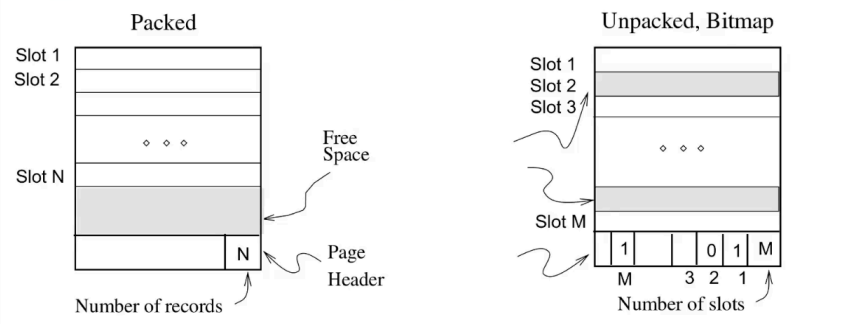
Fixed Length

Record format :



Page Format:

Two ways to format page:



1. We only store the number of slots we need. We need to store this number (N) to be able to add records.

   Faster appending. Slower deletion (need to "compact everything").

2. We store a constant number of slots along with bitmap to see if they are free or not.

   Faster deletion(just mark free). Slower appending.

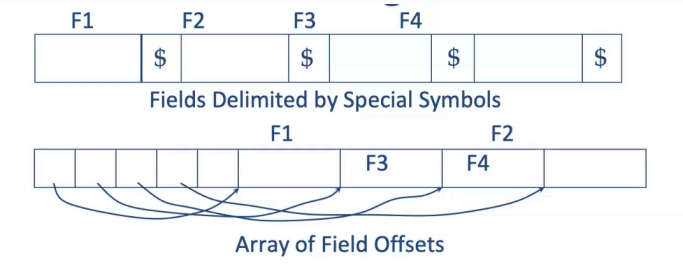
Variable length

We may need to change the size of an attribute.

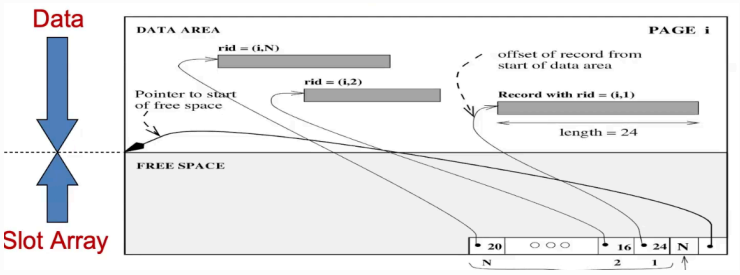
Record format:

Two solutions :

1. Bad: Delimit fields by special symbols(we can't use it in filds later).
2. Good: Store offsets(pointers).

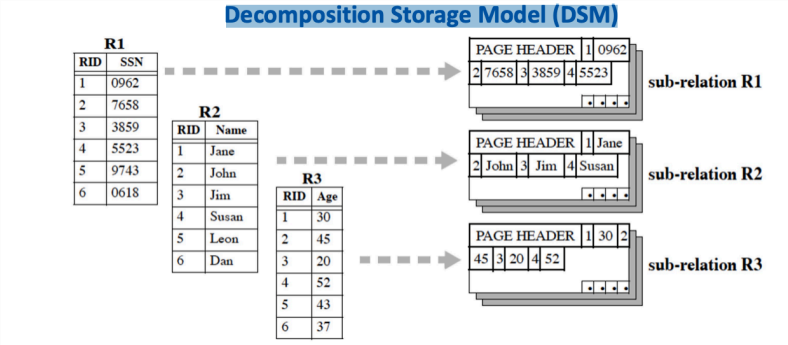


Page format: Much more chaotic:



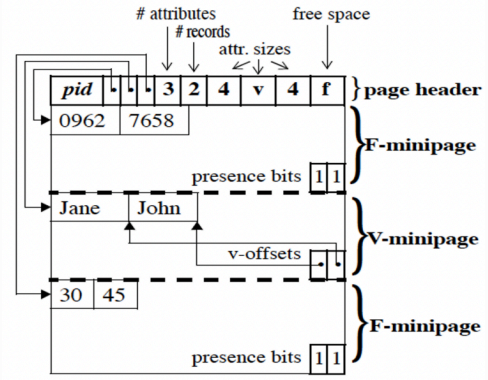
- After deleting and modifying records may not even be in order.
- Good to keep free space compact.

Decomposition Storage Model (DSM): Colum by column storage



Faster for queries on attributes(analytics) e.g average age.

Alternate format: Partition Attributes Across (PAX)



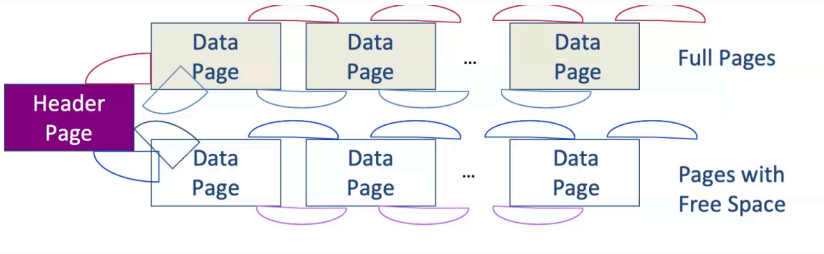
V-minipage: variable length

F-minipage: fixed length

UNDERSTAND DIFF WITH DSM

Alternative file organization

- **Heap files :** a mess, good when retrieving all records. (slow finding, quick insertion). Messy desk.



- **Sorted files:** good for retrieval in some order. (fast finding, slow insertion).

  Organized desk.

- Index File Organization

Lot of write => heap. Lots of read => sorted.

Which is better ? Sorted file or Heap file ?

- Based on IO and considering the **average case**

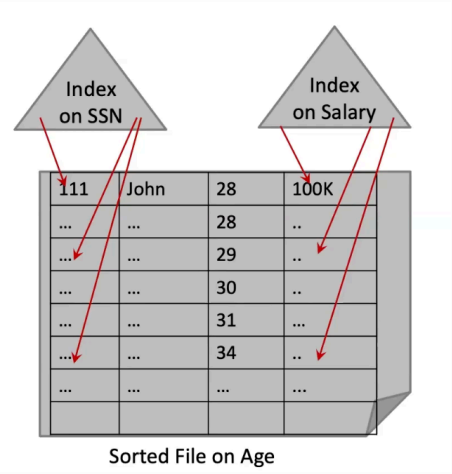
B: Number of data pages

	Heap File	Sorted File	notes...
Scan all records	B	B	
Equality Search	0.5B	$\log_2$ B	assumes exactly one match!
Range Search	B	($\log_2$ B) + (#match pages)	
Insert	2	($\log_2$B) + 2*(B/2)	must R & W
Delete	0.5B + 1	($\log_2$B) + 2*(B/2)	must R & W

Delete: heap: 0.5B to find + 1 to overwrite / sorted: logb to find + b/2 times read and write to "lift" everything one index up.

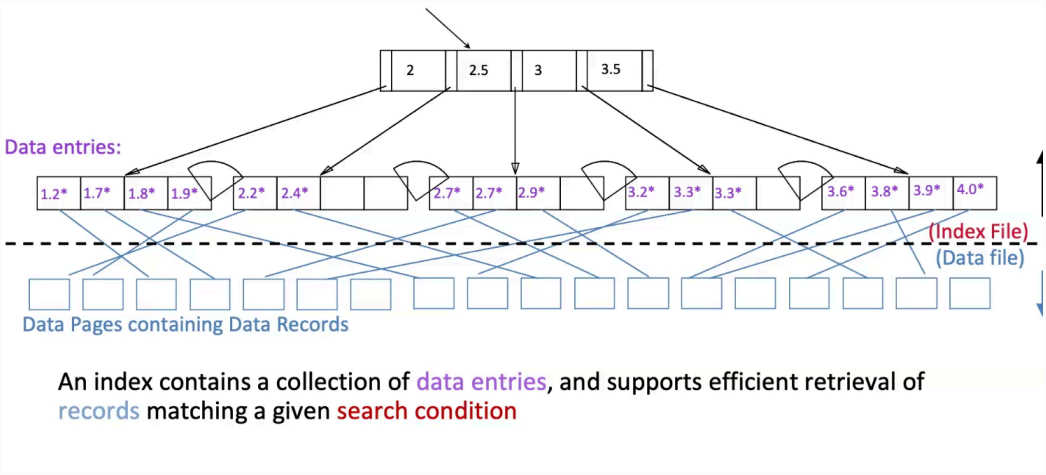
Indexing

Redundant(need for efficiency not correctness) data structure so that we can search the data in a different order that it is stored in our db.



An index on a file speeds up selections on the search key fields for the index

- The search key is NOT necessarily a key (e.g., no need to be unique)

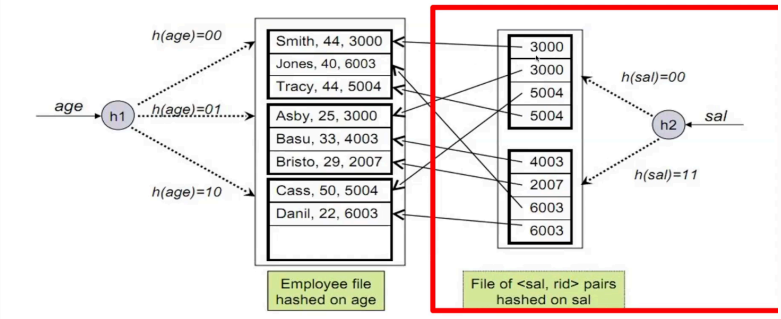


What to put in leaves ? (Data entries) Assume a data entry **k***

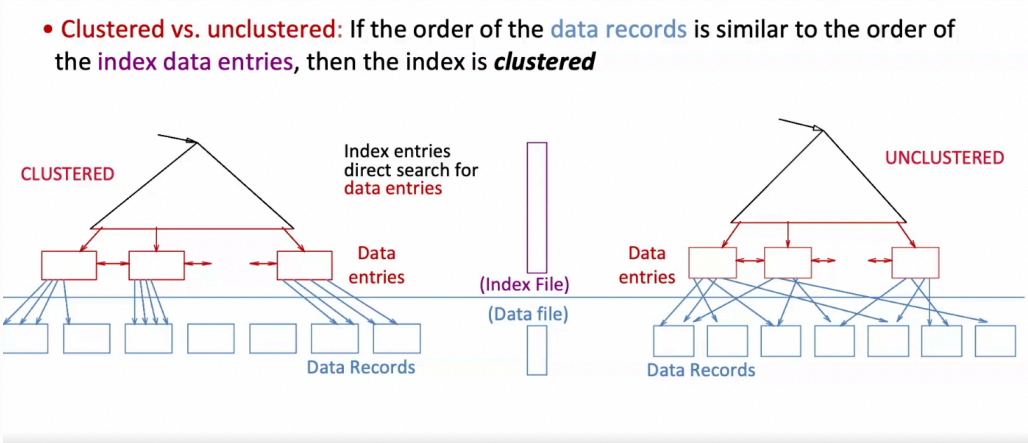
There are 3 alternative representations:

1. Actual data record (with key value **k**)
2. <**k**, matching data record> (uniqueness of search key is needed)
3. <**k**, *list* of rids of matching data records> (like the case above gpa)

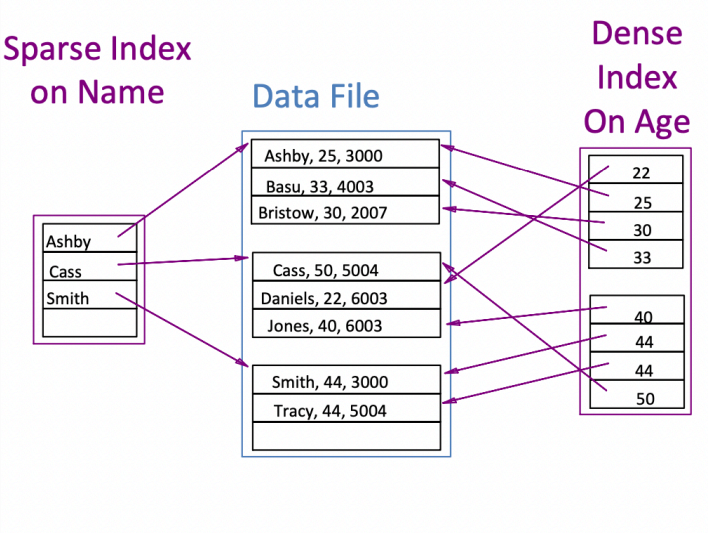
Hash indexing



Clustered vs Unclustered



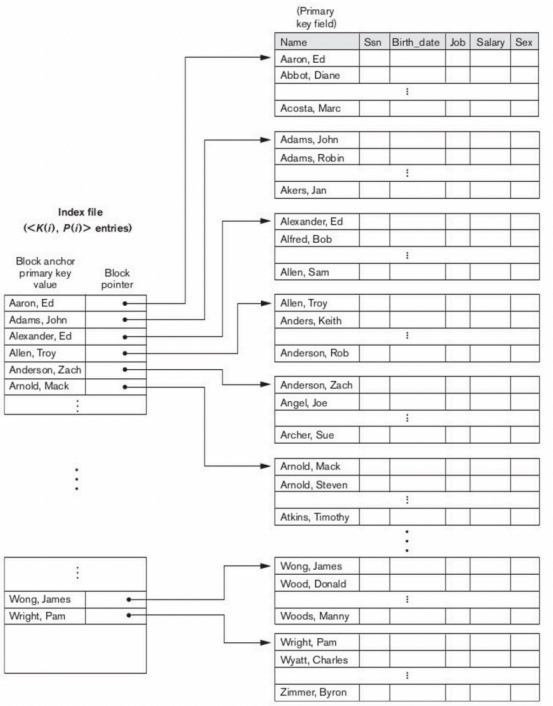
Dense vs sparse



Different types of index

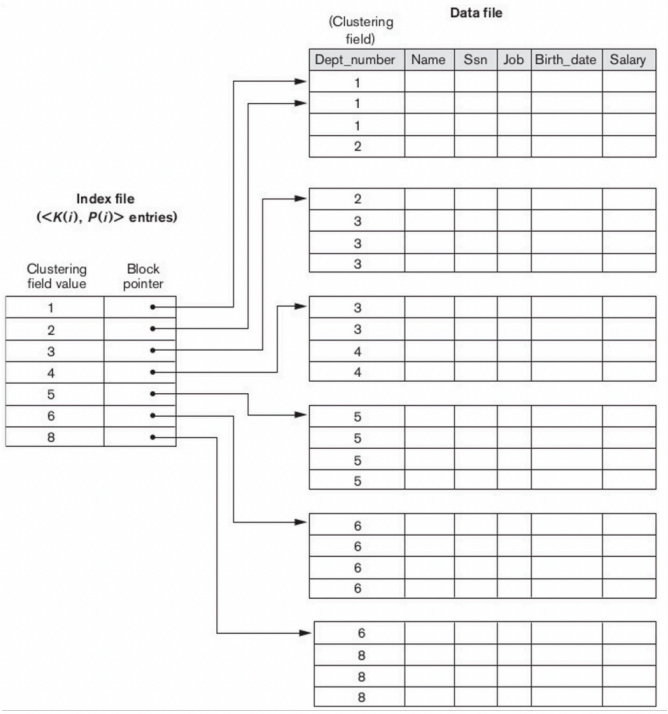
Primary index

- Indexing Field = Key
- File is physically sorted on indexing field
- One index entry *per block*
- Index pointers can be block pointers (anchors)
- Sparse Index



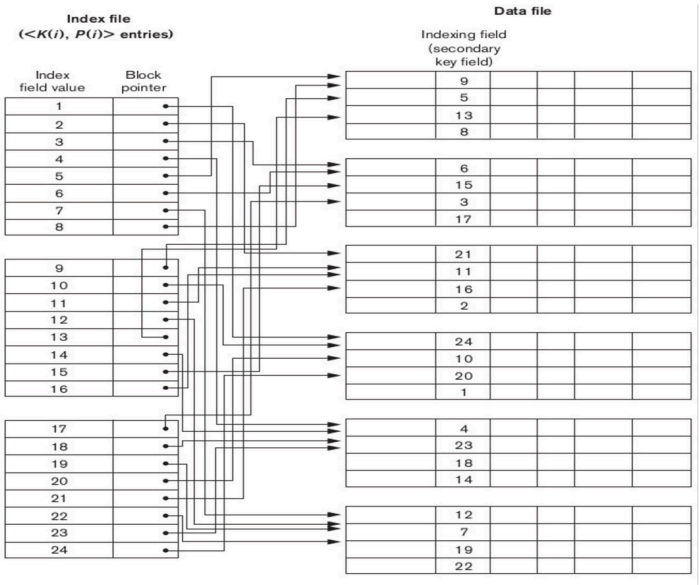
Clustered index

- Indexing Field = Non-Key
- File is physically sorted on indexing field
- One index entry *per distinct value*
- Index pointer is block pointer to first block with the value
- Sparse Index



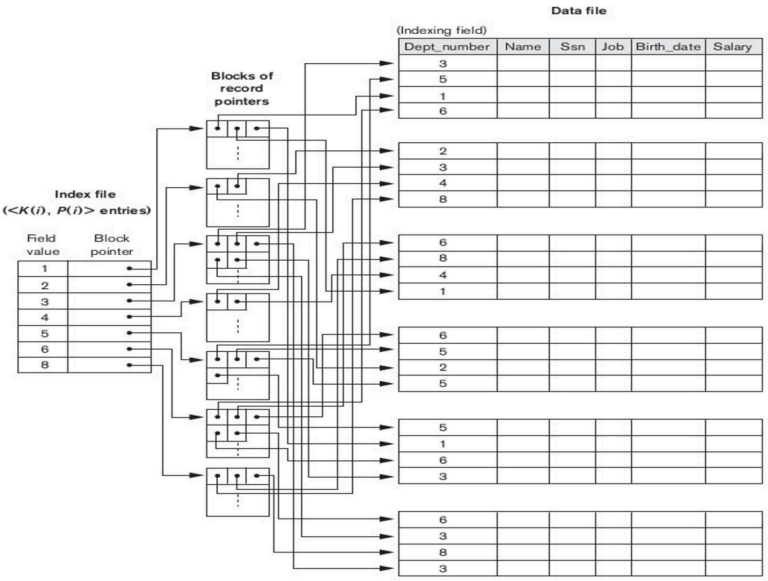
Secondary key index

- Indexing Field = Key
- File is **NOT** physically sorted on indexing field
- One index entry *per record*
- Index pointer is record pointer
- Dense Index



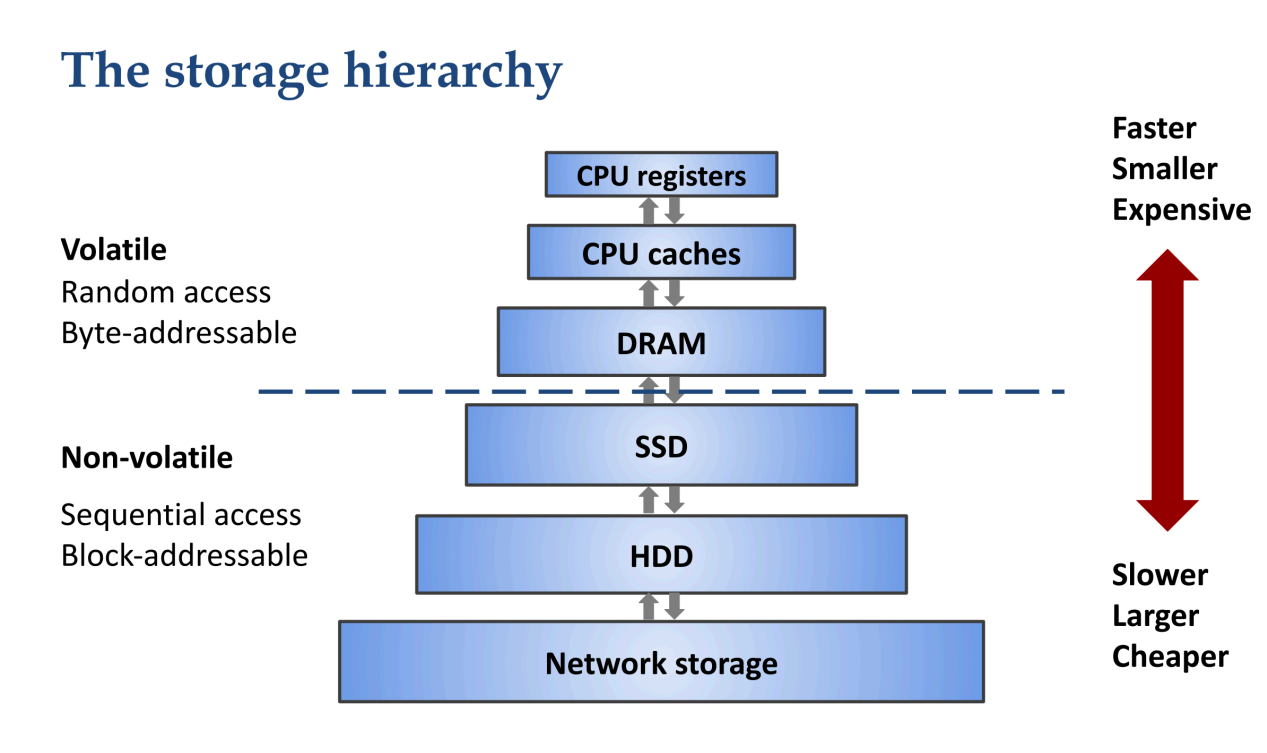
Secondary non key index

- Indexing Field = Non-Key
- File is **NOT** physically sorted on indexing field
- One index entry *per record*
- Index pointer
  - One per record (dense)
  - One per value (sparse)
    - Variable-length record
    - Extra level of indirection



Type of Index	Indexing Field	File physically sorted on indexing field?	Index Entries	Index Pointers	Sparse or Dense?
Primary	Key	Yes	One per block	Block anchor	Sparse
Clustering	Non-Key	Yes	One per value	Block pointer	Sparse
Secondary Key	Key	No	One per record	Record pointer	Dense
Secondary Non-Key	Non-Key	No	One per record/ value	Record pointer/ Variable length/ indirection	Sparse or Dense

Week 4: The storage layer



Remark:

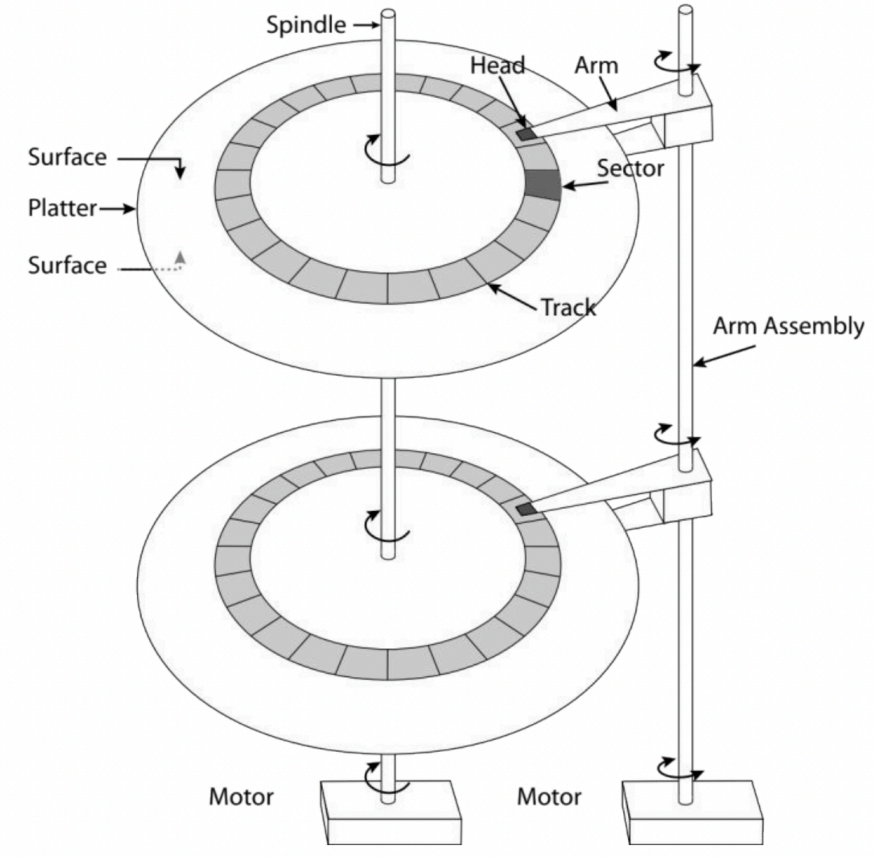
- The non-volatile area is **block-addressable**. It is store in Disks (as opposed to CPU and main memory for volatile area)

DBMS stores information on disks. This has major implications for DBMS design:

- READ: transfer data from disk to main memory (RAM)
- WRITE: transfer data from RAM to disk
- Both are high-cost operations, relative to in-memory operations, so must be planned carefully!

So disks are slow, there are two types of disks, Magnetic disks(hdd) and flash memory(sdd). HDD is cheap, slow for random access and has good performence for streaming. SDD are more expensive and have medium performence for random access.

HDD



- **Track**: concentric circles on the disk
- **Sectors**: slice of a track; smallest addressable unit
- **Cylinder**: All the tracks under the head at a given point on all surfaces

Disk overhead

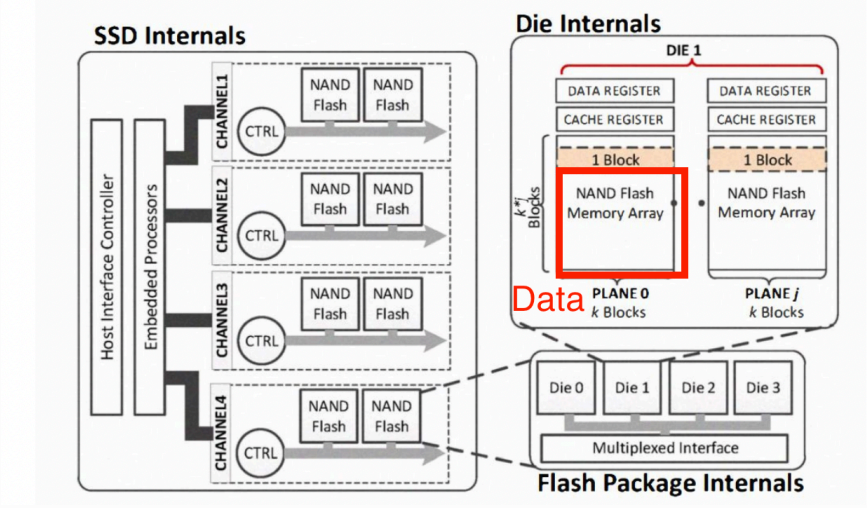
Disk latency = Seek time + Rotation time + transfer time

- **Seek**: position the head/arm over the proper track To get to the track (5–15 ms)
- **Rotational delay**: Wait for desired sector to rotate under read/write head (4–8 ms) *Only need to wait for half a rotation on average.*
- **Transfer time**: Transfer a block of bits (sectors) under read/write head (25–50 usec)

Seek cost is usually the highest.

Using disk efficiently: Minimize seek time and rotational delay.

SSD

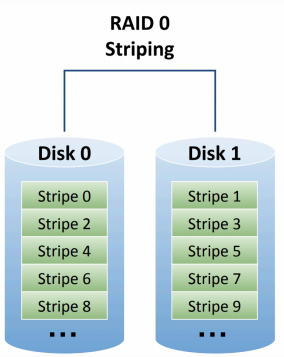


Hierchical architecture for better parallelism.

SDD have a "fast" random access.

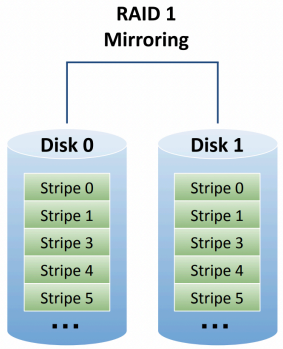
Redundant Array of Inexpensive Disks (RAID)

RAID0



- Best performence (parallel reads/writes)
- No security
- Total storage capacity: sum of capacities of all disks

RAID1

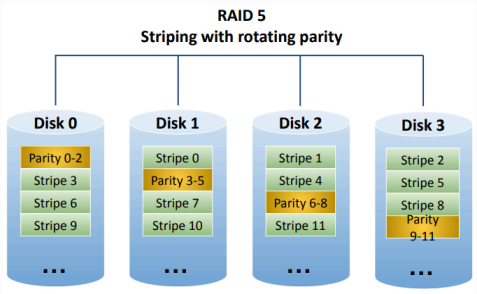


- Deals well with disk loss
- Does not handle corruption
- Total capacity: capacities of one disk => expensive

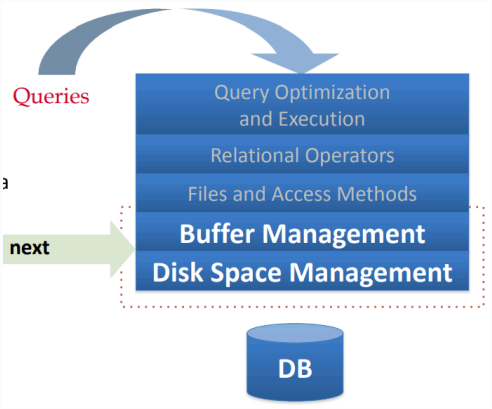
RAID 5

Parity: Another mechanism for fault tolerance. $P_{i-j} = S_i \oplus S_{i+1} \oplus \ldots S_j$

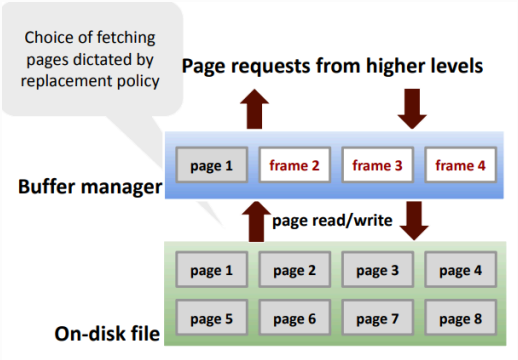
- If one disk fails, one can reconstruct its data by XOR-ing all remaining drives.
- Fast: Parallism (3 times faster than one disk, N=4)
- Capacity : $\frac{N-1}{N}$ where N is the number of disks. => Affordable



Buffer management



Data lives in the disk. However, we need it to be in DRAM to operate on it. So how do we manage which data to put on DRAM and how ? **buffer manager**



Buffer pool is organized as an array. Each entry of the array is a **frame**. So a frame contains a page along with this page's metadata (information needed by buffer manager e.g dirty bit,pin...)

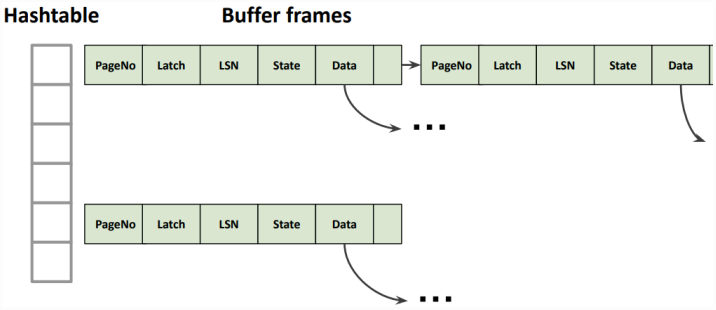
Each frame holds other information :

- State : Clean/dirty/new created ...

  dirty flag If page has been modified after it was imported from disk.

- **Pin/reference counter:** A marker or a counter indicating if a page is being referenced by higher levels of DBMS.

For faster search in the buffer, we have a page table.



Getting a page to the pool when requested ...

1. Checks the buffer pool to see if some frame contains the requested page, and if so increments the pin count of that frame. If the page is not in the pool, the buffer manager brings it in as follows:

   (a) Chooses a frame for replacement, using the replacement policy, and incre- ments its pin count.

   (b) If the dirty bit for the replacement frame is on, writes the page it contains to disk (that is, the disk copy of the page is overwritten with the contents of the frame).

   (c) Reads the requested page into the replacement frame.

2. Returns the (main memory) address of the frame containing the requested page to the requestor.

Replacement policies

- First in-first out (FIFO)
- Least recently used (LRU)
- Clock

Clock : An approximation of LRU that does not need a separate timestamp per page. Each page has a reference bit. When a page is **accessed**, set it to 1.

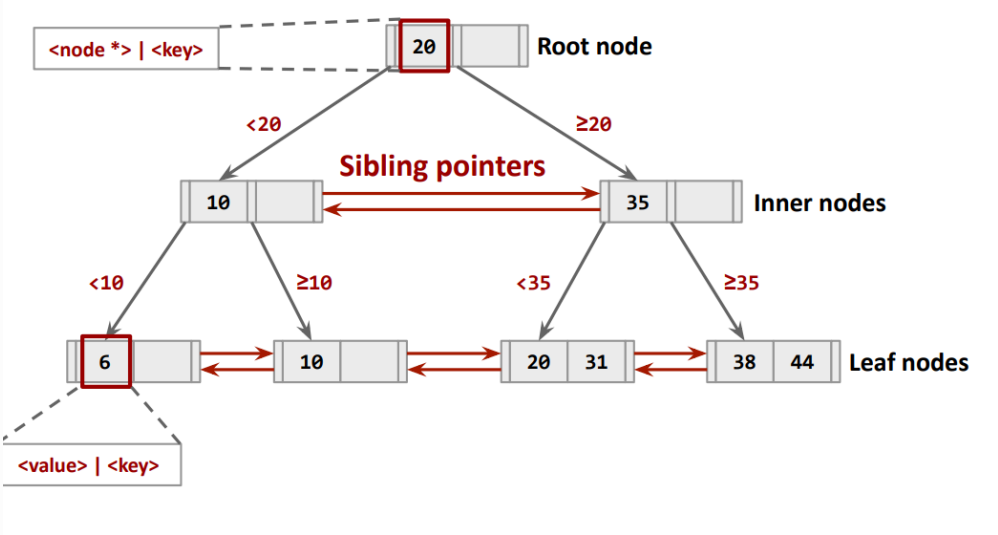
Organize the pages in a circular buffer with a “clock hand” :

- Upon sweeping, check if a page’s bit is set to 1
- If yes, set to zero If no, then evict.

> **Clock:** To stay, you must be accessed each circular turn.

Week 5: B+ Tree

A self-balancing (height balanced), ordered tree data structure that allows *searches*, *sequential access*, *insertions*, and *deletions* in $O(log_F N)$.



- **d** : max number of keys per node (in the above example=2)
- **F** : fanout- # of children of each node (=2 for root node in above example)
- **Balancing:** To maintain the tree balanced we conserve the following invariant:

> *Each node must be atleast half full :* $d \leq \#\text{keys} \leq 2d$

Operations on B+tree

- Search : Most straighword
    1. Start with the root node
    2. Is the current node a leaf?

       If yes, return the current page (locate the entry on it)
    3. Find the first entry >= search key (binary search)
    4. If no such entry is found, go to the upper node, otherwise go the corresponding page
- Insert :
    1. Find correct leaf node L
    2. If not empty, insert in the correct (sorted) order.

       Else:

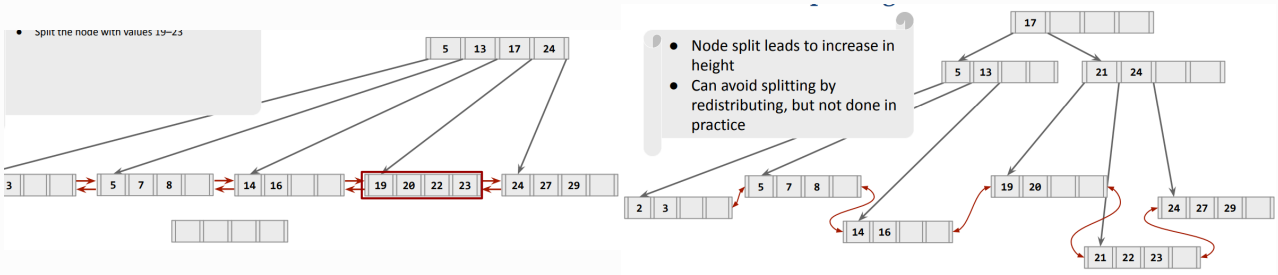
2.1. Put half of L into a new leaf node L_2

2.2. Insert L_2 to the parent of L (so L and L_2 are at the same level)

2.3 This insertion happens the same way recursively

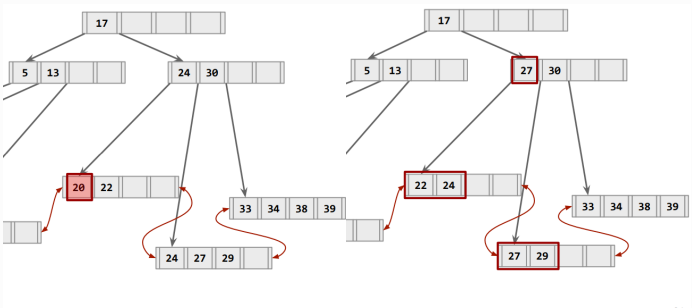
Example : Insert 21:

:

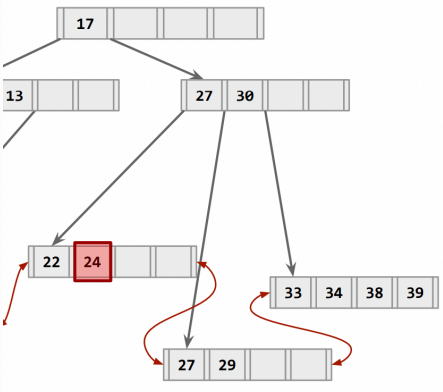


- Delete :

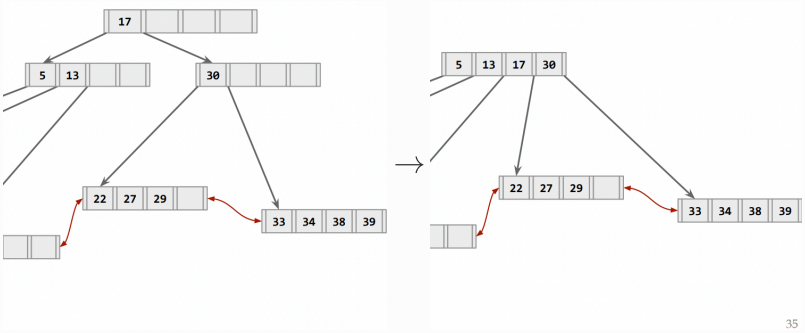
1. Find correct leaf node L
2. Remove entry
    1. if node is atleast half full $\longrightarrow$ done
    2. Otherwise: Borrow from sibling with same parent
        1. If sibling more than half full $\longrightarrow$ done



        2. if sibling less than half full $\longrightarrow$ Merge



We may fidn ourselves in the case were parent is not half full. It this case, we rebalance recursively.



We can also merge with root.

B+Tree design choices

- Node size : The slower the storage device, the larger the optimal node size for the tree.
- Merge threshold : In pratice we keep 67% occupancy (insteaf of half).
- Variable length keys
- intro-node search : Linear search (performence by simd instruction) or binary search or interpolation.

Concurrency on B+Tree

- Can't just lock node by node because you need to also modify parent
- **Lock coupling**

  Lock node and parent

  E.g. Latch the root first, latch the first level, release the root, latch the second level etc

  problem: when you need to propagate up the to the root.

  Alternative approach: Use restart or optimistic coupling

  1. First try to insert using simple lock coupling
  2. If we do not split the inner node, everything is fine
  3. Otherwise, release all latches
  4. Restart the operation, but now hold all the latches all the way to the root
  5. All operations can now be executed safely

Week 8 Hashing and sorting

In building hash tables, we want datastructures that have average constant time and worst case linear time for operations like insert, delete, search.

Aproach 1. Linear probe hashing

Insertion

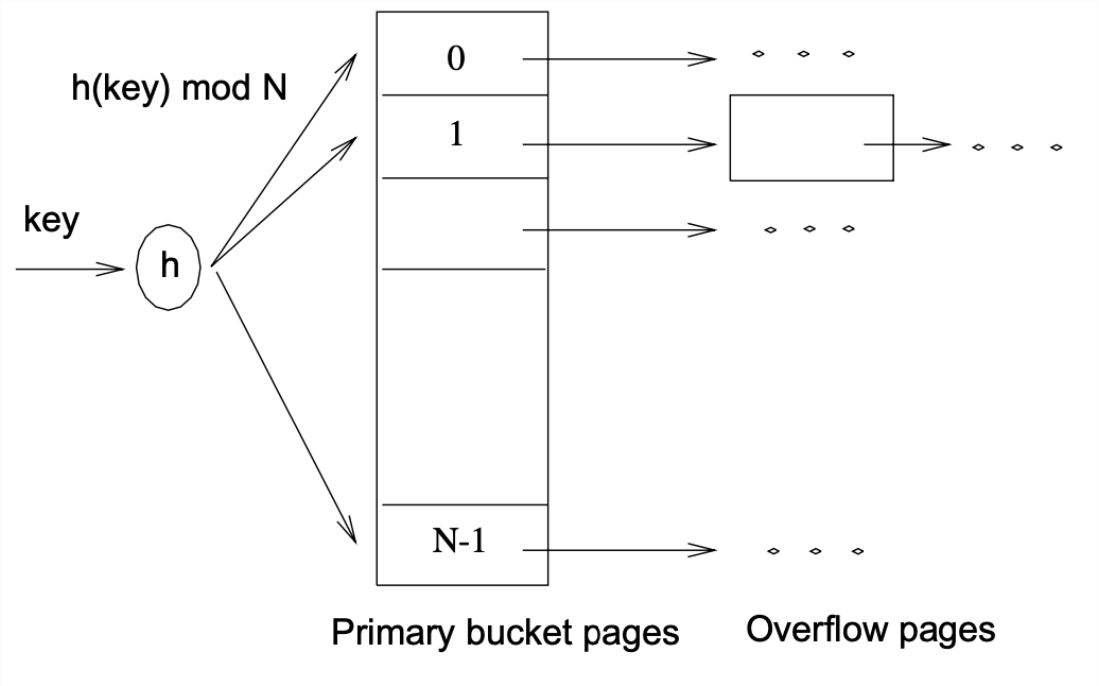
- Use the output of hash function $h(key)$ as a index.
- If that index is full, use check next index and so on.

Searching is similar to insertion, we search starting from the index $h(key)$.

For Deletion, we search for the element, then mark its index as deleted(we call this a *tombstone*).

❌ All operations are O(N) in the worst case. ❌ This approach also assumes when know beforehand the maximum size of data we want to store.

Approach 2. Chaining



- Choose bucket $h(key)$, if it is full consider the linked overflow pages.

The numbef of buckets is **fixed**

❌ If the file grows a lot, many pages to traverse(and read) to find data.

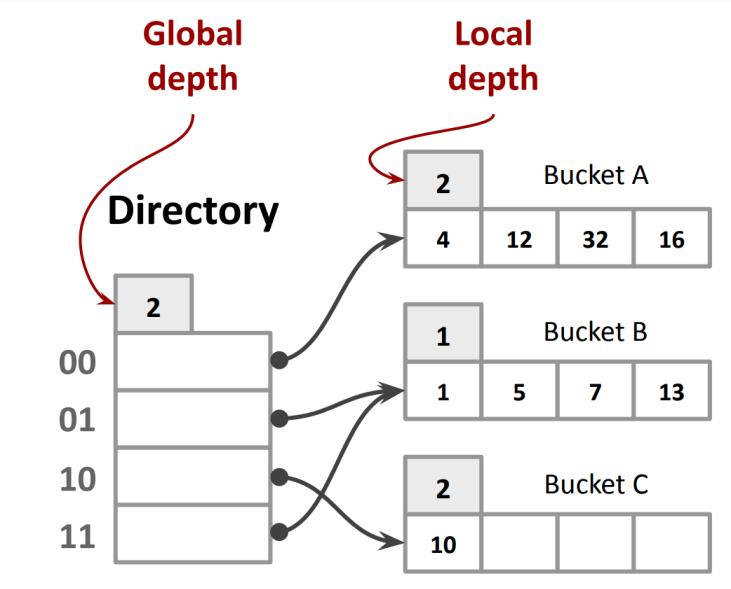
❌ If file grows, we waste space and rehashing(rebucketing) is very expensive(read hole file)

Solution **Dynamic hashing**

Extendible hashing

Idea, if a bucket gets too big, we split it.

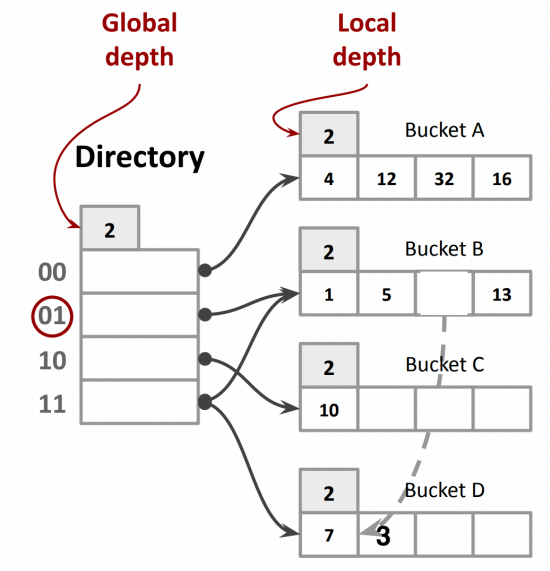
So we are in the following setting :



We save the bucket of each hash values with distinct 2-LSB (2 because it is the global depth).

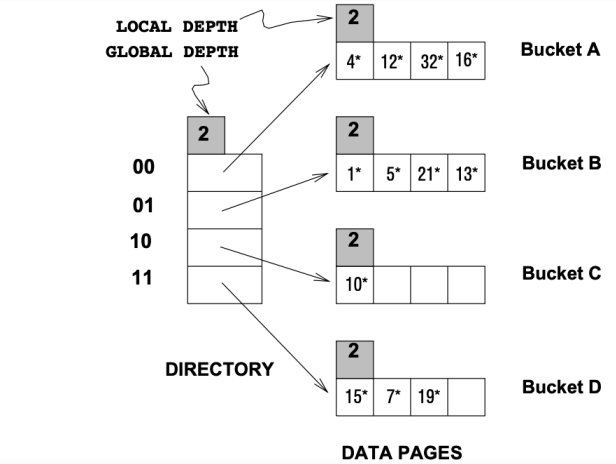
For example, we have in total 4 values with 2-lbs = 01 or 11, they all have as lsb 1. So we save this in same bucket(B), this bucket has element which has the same 1-lsb (so it has local depth 1).

- if we were to add (a key hashed to) 3, for example, then bucket B would overflow, we would then to split it into two buckets. We use as criteria to decide 2nd lsb. We would get :

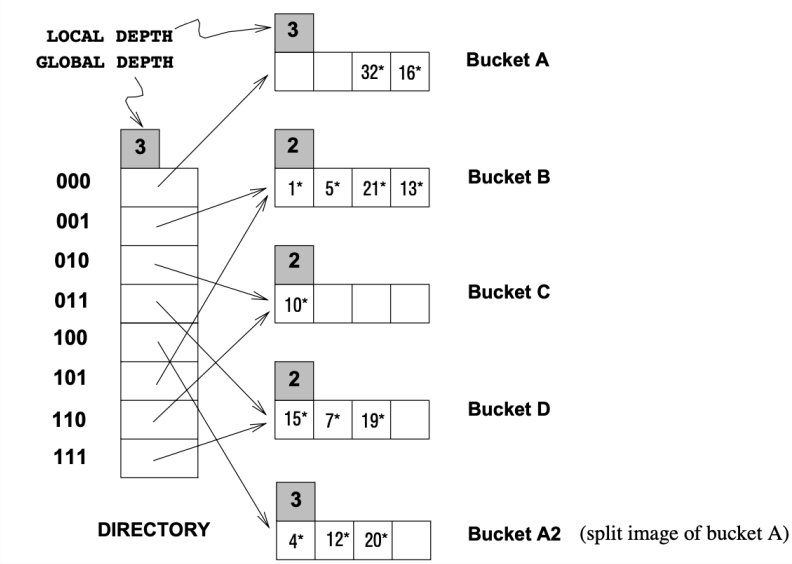


Notice that in this case, we do not read to add buckets.

- *When local depth = global depth and we have an overflow* (if we want to add 20 in the below example)



Then we will need to operate with a local depth of 3. Therefore, we double the number of buckets and increase the global depth. So we get the following :



Even if we can have dynamic buckets, we still can have collisions ❌ They should be handled seperately (with overflow pages).

Linear hashing

We have many hash functions $h_0, h_1, h_2, h_3 \ldots$ such that the range of h_{i+1} is double that of h_i, we can image they all "come" from a mother hash function hash function $h : h_i(x) = h(x) \mod N2^i$

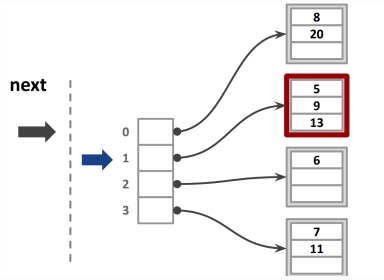
This algorithm proceeds in rounds, let's say we are at round $round$

- We say we *split* a bucket, when we create a new bucket and know use $h_{round+1}$
- At each round all buckets will be eventually split.

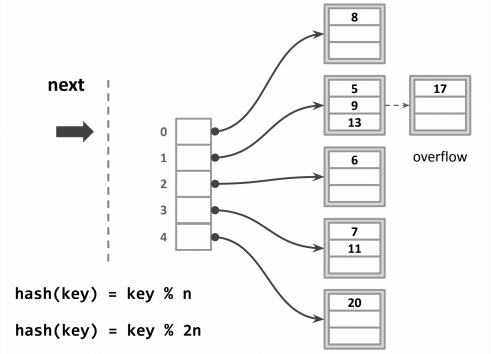
At each round there are $N2^{round}$ buckets and we keep track of a variable $next$ which represents the next bucket to split. If there is an overflow, we add an *overflow page* and we **split bucket** $next$ and increment $next$.

So if we have an operation, say insertion, we check if the hash (with is h_{round})$\leq next$, in which case this bucket is not split and we can access. If otherwise, meaning $> index$ then it means content of this bucket can be in $h_{round}(x)$ or $2h_{round}(x)$ we know that by looking at $h_{round+1}(x)$.

Insert 17 :



Triggers *split* of bucket $next = 0$



8 and 20 have same output of h_{round} but not $h_{round+1}$

✅ avoids directory structure of Extensible hashing.

✅ In extensilble hashing, when we "split" (and exceed global depth) we need to double buckets. Here we do it much less.

Sorting

2-way external merge sort

2-way meaning that in each pass we can only consider two pages. Meaning our buffer will contain 3 pages, 2 for input and one for output.

Pass 0 : Load page, sort page, repeat $\rightarrow$ we get N sorted pages.

Pass 1 : Load two pages, merge them, go to next pair $\rightarrow N/2$ sorted pages.

In 2 way merge sort we do

> $1 + \lceil \log_2(N) \rceil$ **pass** and the **total IO cost** is $2N(1 + \lceil \log_2(N) \rceil)$ (in each pass we read and write N page)

where N is the numbere of pages to sort.

B-way exteral merge

In real life, we have more than 2 pages in the buffer, let's say we have B buffers.

Pass 0 : Load B page, sort them , repeat page $\rightarrow$ we get $\lceil N/B \rceil$ runs of sorted B pages.

Pass 1 : Load first page of the $\lceil N/B \rceil$ runs available(we can only load $B-1$), merge these, go to next batch of $B-1$ among the remaining runs $\rightarrow$ we get $\lceil N/B \rceil / (B-1)$ runs ...

> Passes : $1 + \lceil \log_{B-1} \lceil N/B \rceil \rceil$
>
> IO Cost : $2N^*(1 + \lceil \log_{B-1} \lceil N/B \rceil \rceil)$

Using a B+tree

If the table that must be sorted *already* has a B + Tree index on the sort attribute(s), then we can use that to accelerate sorting

• Retrieve records in desired sort order by simply traversing the leaf pages of the tree

Consider the case:

- Clustered B+ Tree: Good idea ✅
- Unclustered B+ Tree: Could be a very bad idea ❌

Week 9 Relational operators evaluation (Query processing)

We will see how to implement(evaluate) relational operators like project, select or join.

However, that is not sufficient to make for optimized query processing. We should also make an efficient query plan. This includes rearranging the operational operations and choosing a physical plan(the actual algorithms that will be excecuted). This will be seen in next chapter.

A DBMS **processing model** defines how the system executes a query plan.

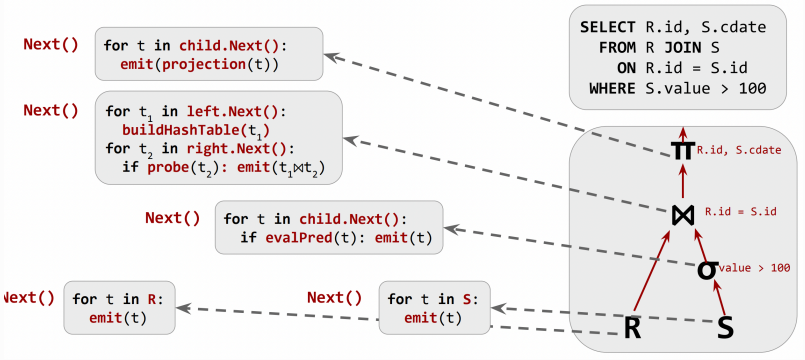
Two approaches:

1. Iterator model
2. Materialization model

Iterator model

- **Next** each call to next return either a *tuple* or *eof*
- An operator implementating Next will call Next on its children

Each operator implementation also has Open() and Close() functions Analogous to constructors and destructors, but for operators.



This process will happen tuple by tuple.

✅

- Pull-based: No operator synchronization issues
- Can save cost of writing intermediate data to disk
- Can save cost of reading intermediate date from disk

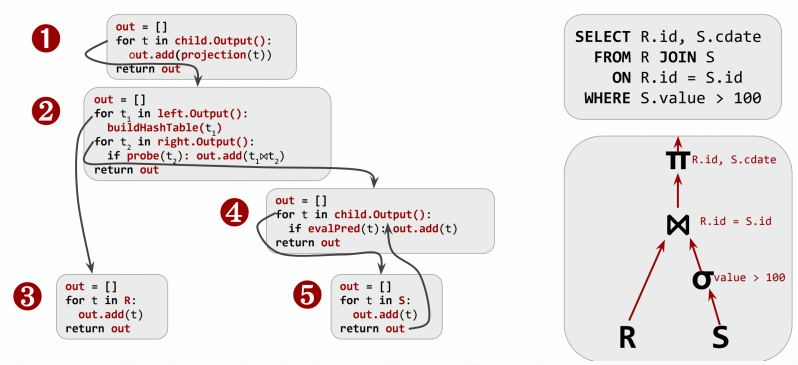
Used by almost every DBMS

❌ Many operators must block until their children emit all their tuples: • Joins, aggregates, subqueries, order by **overhead**

Materialization model

The operator “materializes” its output as a single result

- DBMS can push down hints (e.g., LIMITS) to avoid scanning too many tuples
- Can send either a materialized row or a single column



✅

- Lower execution / coordination overhead
- Fewer function calls

❌

- Not good for analytical queries with large intermediate results
- Requires memory and sometimes it won’t be enough

Access methods

An access method is the approach how a DBMS accesses the data stored in a table.

Simple selection

```
SELECT *
 FROM Reserves R
 WHERE R.rname < 'C%'
```

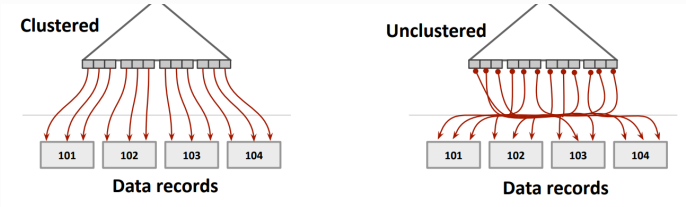
Of the form $\sigma_{\mathrm{R.attr\ op\ value}} R$

Size of result approximated as **size of R * reduction factor**

• Reduction factor also known as selectivity

Methods (we consider relation R with M = 1000 pages and 100K record as example):

- **No index, unsorted** : Scan the whole relation Cost is **M** (# pages)
- **No index, sorted:**
  - Cost of binary search + number of pages containing results
  - For reserves = **~10 IO + [selectivity * #pages]** (110 for 10% selectivity)
  - This is rare; most likely an index will definitely exist
- **With an index on selection attribute**
  - clustered ≈ **[selectivity** × **#pages]** (100 IO in this case) ✅
  - unclustereed ≈ **[selectivity** × ***#records*****]**(10K IO) ❌



Selection

We consider `day < 8/9/94  AND bid=5 AND sid=3`

Approach 1.

Assuming we have an **b+tree on day** (or on <day,other_attribute>)

We can retrieve all records corresponding to `day < 8/9/94`

Then check the other conditions (bid =5 and sid =3)

Approach 2.

If we have more than a **b+tree** on day, for example we **also** have **hash index on sid**

Retrieve from b+tree satisfying `day < 8/9/94`

Retrive from index satisfying `sid=3`

Retrieve records and check `bid=5`

Projection

```
SELECT DISTINCT
 R.sid, R.bid
 From Reserves R
```

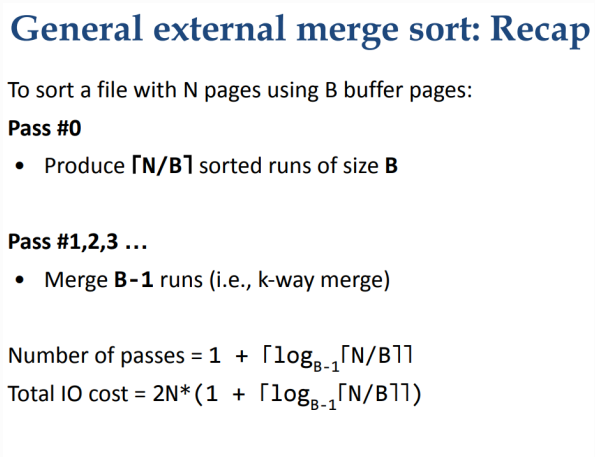
I. Basic approach is to use sorting

a. Scan R, extract only needed attributes

b. Sort the resulting set

c. Remove adjacent duplicates

recap about merge sort :



Total cost = 2N * #passes

Cost:

a. Keep only needed attributes (25% of pages so 250pages) → 1000 reads + 250 writes.

b. Sorting with 20 buffer page takes 2 passes $\rightarrow$ IO = 2 * #pages * #passes = 2 * 250 * 2

c. Remove adjacent duplicates $\rightarrow$ 250 to read

Total is 2500 IO.

II. Optimization : **modify external sort to project and eliminate duplicate on the fly**

a. pass0 of external sort also eliminates unwanted attributes. $\rightarrow$ 1000 read + 250 write

b. Merge the $\lceil N/B \rceil$ runs in $\lceil \log_{B-1} \lceil N/B \rceil \rceil$ passes and eliminate duplicates while merging $\rightarrow$ 250 (we don't take final writing into account for some reason)

So total is 1500 IO.

III. Projecting with hashing

We have B buffers and $h_1 : keys \rightarrow \{1, \ldots, B-1\}$, so we will have $B-1$ partition.

We will work in two phases.

1. Partioning phase
    - read R using a buffer
    - for each tupe: discard unwanted filed **then** apply hash function h_1 to send it into one of the $B-1$ partition.
        - result : $B-1$ partion where tuples in different partitions are **guaranted** to be different(otherwise h_1 would hash them the same)⚠️
2. duplicate elimination
    - read partition and build in memory hash table with $h_2 (\neq h_1)$
    - do duplicate elimination
    - 😕 If it does not fit in memory partition recursively.

Assumptions in numbers:

- h_1 distributes tuples uniformly.
- let T be #pages after projection

- #pages per partition = $T/(B-1)$
- A partion fits in memory $\implies B \geq T/(B-1) \implies B > \sqrt{T}$

Joins

I. Simple nested loops

```
foreach tuple r in R do //  R is the outer relation
 foreach tuple s in S do
    if ri==sj
then add<r,s> to result
```

- M the number of pages in R , and p_r tuple per page
- N the number of pages in R

IO cost (ignoring output) = M + $M \times p_r \times N$

Because for each tuple in R (Mp_r of them) we read N pages. (assuming only 1 buffer page)

⚠️ choice of inner/outer matters

II. Index Nested Loops Joins

If we have an index available, we can use Index nested loops

```
foreach tuple r in R do
  foreach tuple s in S where ri== sj do
    add <r, s> to result
```

IO cost : M + $M \times p_r \times$ cost of finding matching S tuples

The cost of finding S tuples can be :

- 1 IO for matching **page** of tuples (clustered)
- 1 IO for each matching tuple (unclustered, it would be equivalent to simple nest join)

III.Page-Oriented Joins

```
foreach page pr in R do // R is the outer relation
    foreach page ps in S do // S inner relations
        for each tuple r in pr do // once we loaded two pages,
            for each tuple s in ps do // we read entries off them
                if r == s then
                    add <r, s> to result
```

IO cost (ignoring output) = $M + M \times N$

We do not read all S for each tuple in R now but for each page.

⚠️ Choice of inner/outer matters.

IV. Block nested loops

What if we have more main memory buffers ? We can load *blocks* .

We do not read all S for each tuple in R now but for each *block* .

IO cost = M + $\#\text{outer blocks} \times N$ where $\#\text{outer blocks} = \lceil \frac{M}{\text{block size}} \rceil$

```
foreach block blockR in R do // #outer block
  foreach page bS in S do  // N
    foreach tuple r in blockR do
      foreach tuple s in bS do
        if ri ==sj then add to result
```

If we have B pages in the buffers, we must use $B - 2$ pages per block, so we have an extra page for reading a page from r and another extra page for the output.

IV. Hash join

One pass hash join :

We can build a hash table on the required attribute.

```
foreach r in R do // R is the outer relation
    add <r.rid,r> to hash table
foreach s in S do
    if s.sid in hashtable // (with value r)
      add <r,s> to result
```

- Cost: M (outer scan) + N (inner scan)

One pass assumption: Enough memory to store M + hashtable (conditions need to be done in one pass)

Two pass hash join

Suppose we have B pages in the buffer.

1. Partition R and S into $R_1, \ldots, R_k$ and $S_1, \ldots, S_k$ respectively.
2. Consider R_i and S_i and do a one pass hash join on them.

> ⚠️ Steps 1 and 2 should be done with **different** hash functions.

- Cost : $3(M + N)$
    - Partioning 2(M+N)
    - Matching step : M+N

In step 2, we need a buffer page to read a page from S_i and another page for the ouput. The remaning $B-2$ pages are used for R_i . So size $R_i = M/k \leq B-2$. The maximal k we can use is $B-1$ (we need one page to read during partioning phase), so $k = B-1$.

Meaning $B > \sqrt{f * M}$ where f is a fudge factor (accounts for hashtable size)

Problem:

- What if we don't have $B > \sqrt{f * M}$ free buffers ? *recursive partitioning*
- What if a partition exceeds expected size(overflow) ? *repartition with other hash function*

Utilizing extra memory : Hybrid hash join

Sometimes we have more that $B > \sqrt{f * M}$ memory, we can use extra memory to speed up steps 1 and 2.

example with one partition left

Phase 1 (partitioning phase)

• Partition S, but do not write out first partition

• Partition R, directly join first partition R1 with S1

Phase 2 (probing phase)

- Join remaining k -1 partitions

If we can keep t partitions in memory, then we save IO by not writing in step1 and not loading in step2 (we save 2 IO for t/k fraction of partitions)

Suppose we will use k partition and $B > fM/k$, then there are pages left over.

In fact we can save $t = \lfloor \frac{B-(k+1)}{fM/k} \rfloor$ extra partions.

V. Sort merge join

- Scan R and sort in main memory
- Scan S and sort in main memory
- Merge R and S

⚠️ Assumptions: One pass if : Enough memory to store M + N. *Usually not availabe*

Cost: Sort R + Sort S + (M+N)

- M+N if one pass, *usually not the case*
- If we use external merge sort : 2N * (# of passes) + 2M * (# of passes) + N + M
- Refinement :

  When we merge a "run" from R and one from S, check for equality of join

Week 11 Relational Query Optimization

Problem: Given an SQL query, how to convert it to the most optimal *plan* ?

Plan : physical plan (relational algebra plan and physical plan).

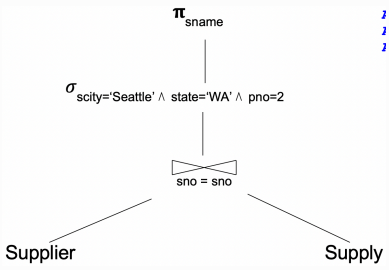
- Step1. **Query transformation** generate logical plan (query to optimized logical formula)
- Step2. **Optimization** Generate physicial plan from logical plan.

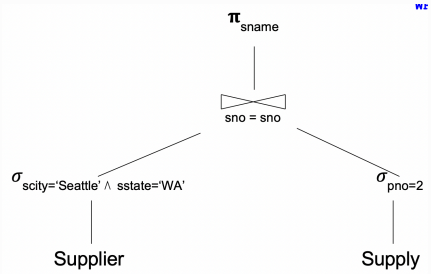
We consider the following SQL query as example :

```
SELECT S.sname
FROM Supplier S, Supply U
WHERE S.scity='Seattle'
AND S.sstate='WA'
AND S.sno=U.sno
AND U.pno=2
```

Query transformation

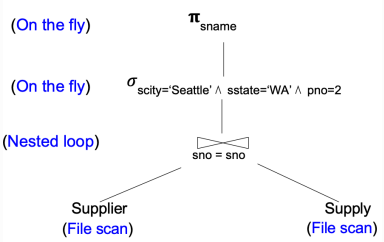
For this query there are many possible *logical* plans (executed from bottom to top) :

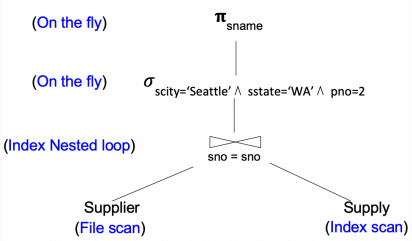




The second plan is better(most of the time), it still depends how it is physicall executed.

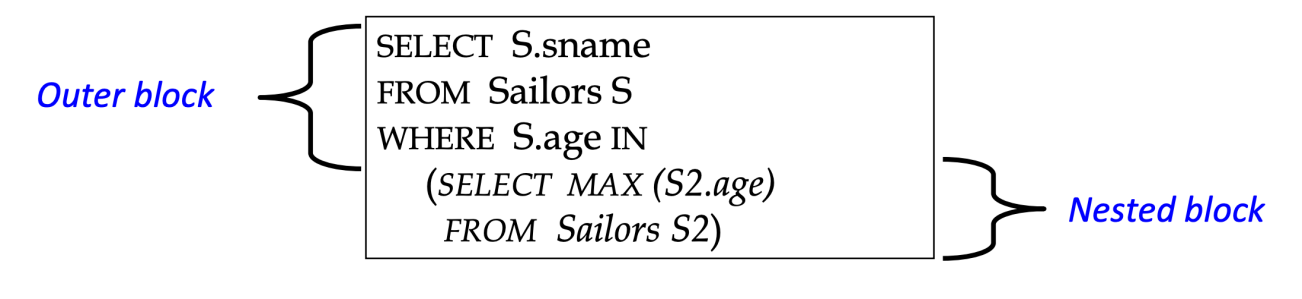
And for each *logical plan* (like the first), there still exsists many *physical plans*(depending on the used algorithms):





This are the steps of query transformation

1. Step 1 : break queries into blocks



2. Step2: Converting each query block into relational algebra

```
SELECT S.sid
FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid AND B.color = "red"
```

$$\pi_{\text{S.sid}}(\sigma_{\text{B.color} = \text{“red”}}(\text{Sailors} \bowtie \text{Reserves} \bowtie \text{Boats}))$$

3. Query rewriting : find the best logical plan

   - Push selection and projection so they are done before join. This is so we reduce the size of the data before joining, which is a costly operation.
   - *Decorrelation*

     Convert query to *uncorrelated* and "standalone query" → nested block can be executed only once.

```
SELECT S.sid
FROM Sailors S
WHERE EXISTS
  (SELECT *
   FROM Reserves R
   WHERE R.bid=103
   AND R.sid=S.sid)
```

Equivalent uncorrelated query:

```
SELECT S.sid
FROM Sailors S
WHERE S.sid IN
  (SELECT R.sid
   FROM Reserves R
   WHERE R.bid=103)
```

   - *Flattening*

     Rewriting a query so we are able to use a join algorithm

```
SELECT S.sid
FROM Sailors S
WHERE S.sid IN
  (SELECT R.sid
   FROM Reserves R
   WHERE R.bid=103)
```

Equivalent non-nested query:

```
SELECT S.sid
FROM Sailors S, Reserves R
WHERE S.sid=R.sid
  AND R.bid=103
```

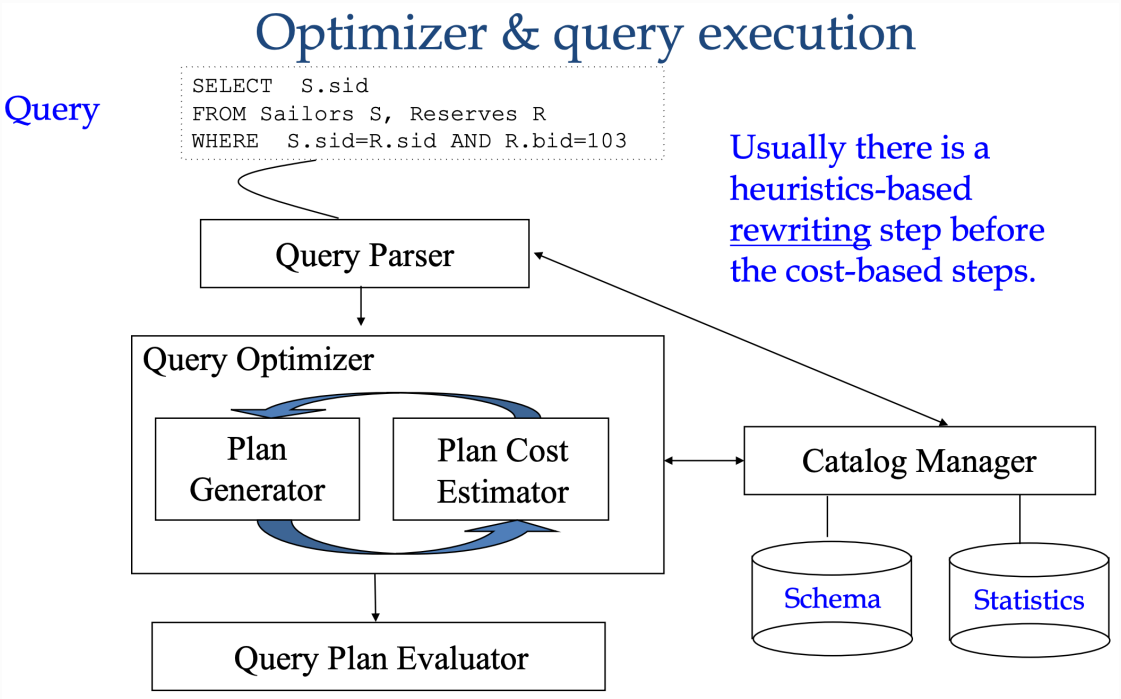
Query optimization

Usuall a **query optimizer** works in the following way

Cost-based query optimization algorithm

1. Enumerate alternative plans (logical and physical)

2. Compute estimated cost of each plan
    - Compute number of I/Os
    - Optionally take into account other resources
3. Choose plan with lowest cost



Week 12 Transaction Management

Ensures :

1. concurrent database access

   Databases receive queries from many softwares, we could execute each set of queries in isolation one by one as they arrive. However, we want better throughput. So we need to do some of them at the same time. However, we also want to guarantee *correctness* and *fairness*.

2. resilience to system failures

   suppose a query is to substract 10$ from A's bank account and add it to B's bank account. If the system fails after first operation, then bank looses money.

   → Guarantee all-or-nothing execution

Solution is **transactions** A transaction is a sequence of one or more SQL operations treated as a unit. It should respect the following :

ACID properties

- **Atomicity**: All actions in the transaction happen, or none happen *("All or nothing")*

  > Note that atomicity here is not the same as the one used in the parallelism and concurrency course.
  >
  > It also implies that if a transaction *aborts* all changes due to this transaction must be *undone*

- **Consistency:** A transaction must preserve consistency if run by itself on a "consistent database". (consistency is defined by user, for a bank transfers in same bank, consistency is the fact that the total amount of money in the bank must remain the same)
- **Isolation:** The execution of a transaction (values read and written), should not be affected by other concurrent transaction.
- **Durability:** If a transaction commits, its effects should persist, even if a crash happens before writing to disk.

Mechanisms to ensure these properties

Atomicity

1. Approach #1: **Logging**
   - DBMS logs all actions so that it can undo the actions of aborted transactions

- Maintain undo records both in memory and on disk

If an abortion happens, just undo → widely used.
Log: list of records with row information, old data and new data.

The are two types of log records, update log records and commit log records.

A transaction is commited once it adds all log recods (update and commit) to disk.

Write-ahead-logging (WAL)

- ⚠️ Log record must go to disk before updating the page
- All **log** records(update and commit record) for a transaction must go to disk **before** the transaction is considered commited.

A log offers an UNDO or REDO operations :

- UNDO: Uncommitted data can overwrite stable version of committed data
- REDO: Transaction can commit before all its all its updates are on the disk

2. Approach #2: Shadow paging
   DBMS makes copies of pages, and transactions makes changes to those copies
   Only when the transaction commits, then page is made visible to others
   Not very used.

Isolation

To ensure Isolation we have **concurrency control** where the the DBMS decides the proper interleaving of operations from multiple transactions. See next chapter. Strict two-phase locking (S2PL) protocol

Durability

How to recover from crash ? 3 steps :

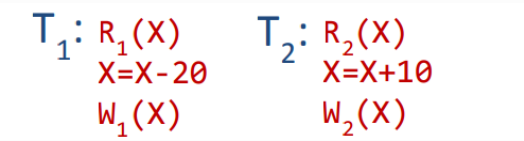
- Analysis: Scan the log (forward from the most recent checkpoint) to identify all transactions that were active at the time of the crash
- Redo: Necessary to ensure than all commited transactions are in main memory.

- Undo: Undo writes of all transactions that were active at the time of the crash, working backwards in the log

Week 13 Concurrency Control I

- **Database:** A fixed set of named data objects (e.g., A, B, C).
- **Transaction:** A sequence of actions (e.g., read(A), write(B), commit, abort).
- **Schedule:** An interleaving of actions from various transactions.

  example:

  T1, T2 are transactions.

  $R_1(x), R_2(X), X = X - 20, X = X + 10, W_1(X)\ldots$ is an interleaving.

Schedules :

- **Serial Schedule:** A schedule that does not interleave the actions of different transactions. $\text{actions}(T_1), \text{actions}(T_2), \text{actions}(T_3)\ldots$

  This lock guaratees correctness. However, it is very slow.
- ***Equivalent* schedules**: two schedules are equivalent if the leave the db at the same state after the execution.
- **Serializable Schedule:** A schedule that is *equivalent* to some serial execution of the transactions.

So any serializable schedule, leaves db at correct state, however, it is not guaranteed that all reads give the correct output.

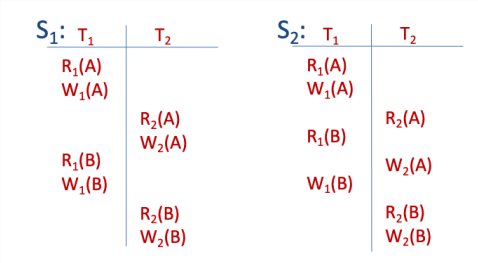
Stronger definition

- **Conflict**: Two operations **conflict** if:
  - They are done by different transactions,
  - And they are done on the same object,
  - And at least one of them is a write

  example : R1 (A), W2 (A) // W1 (B), W2 (B)
- **Conflict equivalence** : Two schedules are **conflict equivalent** iff:

  – They involve the same actions of the same transactions, – And every pair of conflicting actions is ordered the same way.

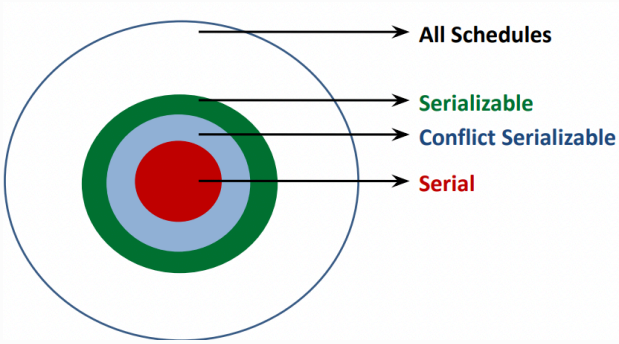
example:



S1,S2 are conflict equivalent, the only two operation that are not in the same order are R1(B) and W2(A).

Note that conflict equivalent $\implies$ equivalent. Meaning conflict equivalence is a stronger property.

- **Conflict serializability** : Schedule S is **conflict serializable** if: – S is conflict equivalent to some serial schedule.

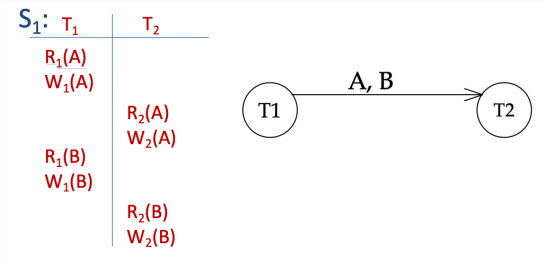


> A schedule S is **conflict serializable** if: – You are able to transform S into a serial schedule by swapping **consecutive non-conflicting** operations of different transactions.

We did an example of this with S1 and S2 above.

Testing for conflict serializability

We use a *precedence graph* : One node per transaction, connect a transaction T_i to T_j if they have conflicting operations O_i and O_j and O_i comes before O_j .



> **Theorem:** schedule is conflict serializable $\iff$ acyclic precedence graph

Two-phase locking(2PL)

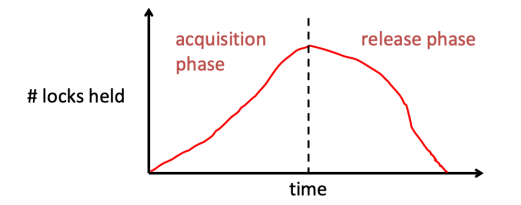
	S	X
S	√	–
X	–	–

Imagine we have writers and readers.

```
reader():                                writer():
  lock(S) -> now writers can't write       lock(X) -> nothing can do shit
  reading...                               write...
  unlock(S)                                unlock(X)
```

Note that a transaction might read and write. ⚠️ In 2PL, all the unlocks happen after all the locks :

```
lock(S(A))
lock(X(B))
write B
unlock(X(B))
read A
unlock(S(A))
```



In other words, A transaction cannot request additional locks once it releases any locks.

So we can't have the following transaction for example :

```
T1      T2
R(A)          -- reads, then releases for write lock to happen
        W(A)
        R(B)
W(B)            -- this is not conflict serializable and cant't happend
```

> **Theorem:** 2PL guarantees conflict serializability. ✅

❌ Problem with 2PL : subject to cascading aborts.

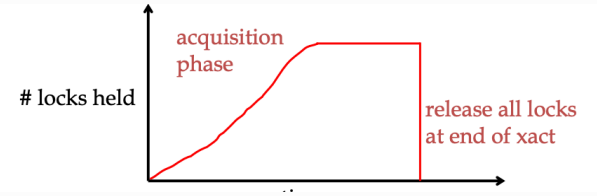
T1: R1(A), W1(A), R1(B), W1(B), Abort

T2: R2(A), W2(A)

this read happens when T1 releases X(A) and S(A) but not S(B) for example

The problem is that if T1 aborts before releasing all locks, T2 must also abort and restart.

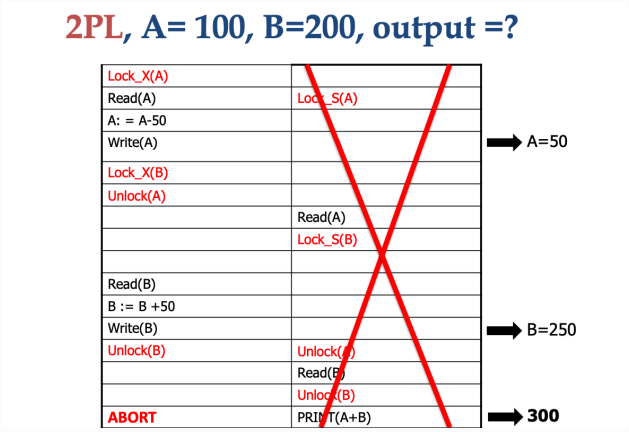
To solve cascading aborts use **Strict 2-PL**: Only release locks after transaction finishes and we are sure it will not abort.

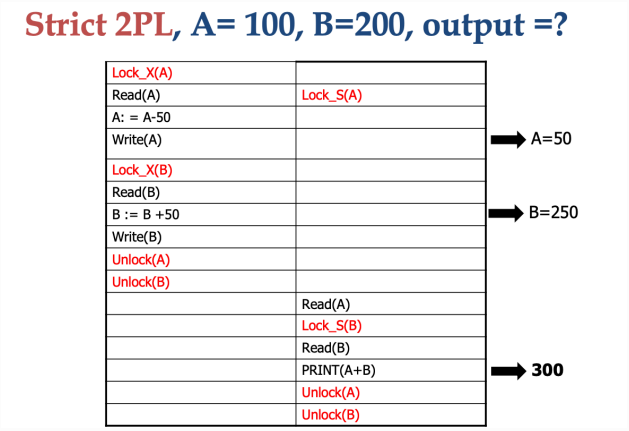


So we only unlock, if we know that either :

- we commited to disk
- we know we need to abord (but no other conflicting transaction started,haha)

Comparions : 2PL vs Strict 2PL

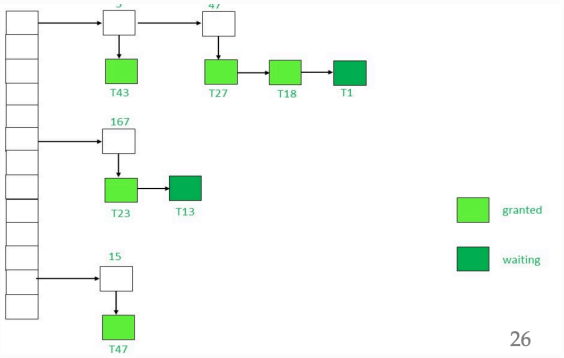




Lock manager: handles Lock and unlock requests.

Lock table entry:

- Pointer to list of transactions currently holding the lock
- Type of lock held (shared or exclusive)
- Pointer to queue of lock requests



Deadlocks

- Deadlock detection

  Create a waits-for graph: - Nodes are transactions - Edge from Ti to Tj if Ti is waiting for Tj to release a lock Periodically check for cycles in waits-for graph

- Deadlock Prevention

  - Assign priorities based on timestamp TSi < TSj => priority(i) > priority(j)
  - Say Ti wants a lock that Tj holds, two policies are possible:

    Wait-Die: If Ti has higher priority than Tj, Ti waits; else Ti aborts(restarts)

    Wound-Wait: If Ti has higher priority than Tj, Tj aborts; else Ti waits(restarts)

    ✅ These schemes guarantee deadlock freedom.

    ⚠️ Important detail: If a transaction restarts, it must be assigned the original timestamp.

Multiple granularity lock

Transactions are very different. For example a transaction who reads a table, needs an S lock on **all the table**, preventing any other transaction to operate on that table, at the same time.
However, consider transactions T_1 that reads half of the rows of a table, and transaction T_2 that writes on the other half of the table, we expect these to be able to run concurrently. For that, we need locks on the **rows** of the table.

$\rightarrow$ we need multiple-granularity(all the db hiearchy) locks.

The protocol :

We introduce other "locks":

- IS – Intent to get S lock(s) at finer granularity
- IX – Intent to get X lock(s) at finer granularity
- SIX mode: S & IX at the same time

Each transaction starts from the root of the hierarchy

- To get S or IS lock on a node, must hold IS or IX on parent node
- To get X or IX or SIX on a node, must hold IX or SIX on parent node
- Must release locks in bottom-up order

I - Multiple granularity lock matrix

	IS	IX	SIX	S	X
IS	√	√	√	√	-
IX	√	√	-	-	-
SIX	√	-	-	-	-
S	√	-	-	√	-
X	-	-	-	-	-

> Notice, that this lock mecanism is theoretically the same as having locks on tuples and then checking that all subgranularities are not locked at each lock trial (check all tuples not S locked if X locking the table). But it makes the lock manager more efficient :
>
> 1. Early Conflict Detection 2. Reduced Locking Overhead

Phantom

Until now, we have been ensuring serializability with S2PL. However, we have been assuming that the database is of *fixed size*, meaning no insertions and deletions are occuring. It is not always the case.

Strict2PL fails to guarantee serializability with insertions and deletions.

Example : Consider T1: “Find oldest sailor”

- T1 locks all records, and finds oldest sailor (say, age = 71)

- Next, T2 inserts a new sailor, age = 96 and commits
- T1 (within the same transaction) checks for the oldest sailor again and finds sailor aged 96!

No serializable scheduling would give that results. We call 96, a *phantom tuple.*

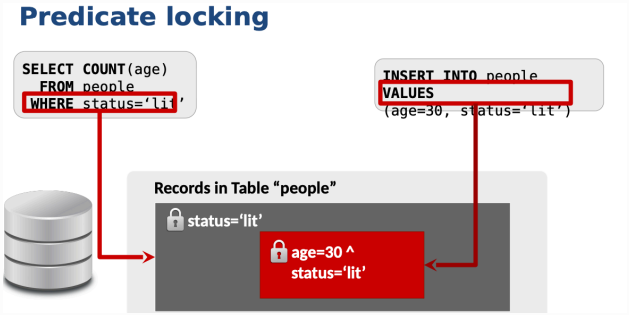
Problem: We lock all **currently existing** records and not the new records.

Approach #1: **Re-execute scans**

Run queries again at commit to see whether they produce a different result to identify missed changes .

Approach #2: **Predicate locking**

Logically determine the overlap of *predicates* before queries start running



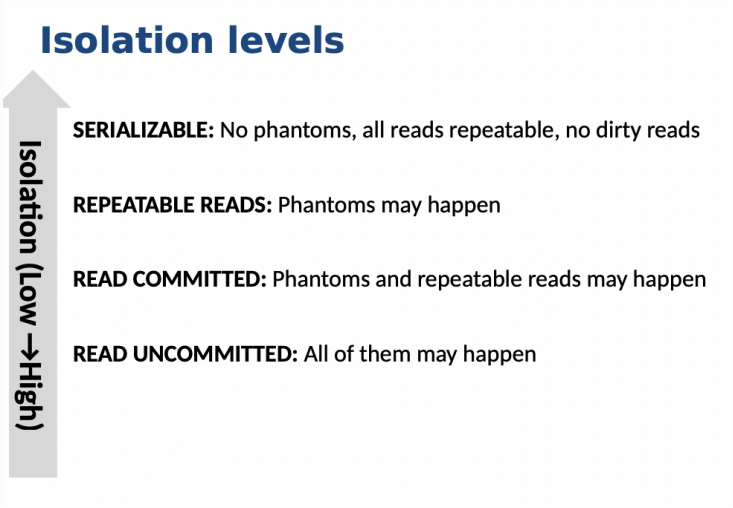
→ S/X locks for *predicates.*

Approach #3: **Index locking**

Use keys in indexes to protect *ranges.*

Isolation levels

We are always requiring serializability, but this is too strong and limits concurrency. There are different levels of isolation.



dirty reads : read uncommited data.

unrepeatable reads : transaction reads same **row** twice and gets different data.

phanton; read same search query twice and get different(due to addition/deletion)

So from easiest to guarantee to hardest : dirty reads, repeatable, phantom