Summary

Table of Contents

    - Joins
    - Comparison and logical operators
    - Set operators

- Other Statements
    - `INSERT` Statement
    - `UPDATE`
    - `REPLACE`
    - `DELETE`
- Views
- More DDL
    - `ALTER`
    - `RENAME`
- Approach for writing SQL
- Files in DBMS
- Indexes
    - Clustered vs Unclustered
    - Primary vs Secondary
    - Single Key vs Composite Key
    - Index Type
- Query Processing
- Relational Operations
    - Selection
- Projection
    - External Merge Sort
    - Sort-based Projection
    - Hash-based projection
- Joins
    - Simple nested loop join
    - Page-Oriented Nested Loop Join
    - Block Nested Loop Join
    - Sort-Merge Join
    - Hash Join
    - General Joins

- Query plan
- Query optimisation steps
  - Break query into blocks
  - Relational algebra equivalences
  - Statistics and Catalogs
  - Cost Estimation
  - Reduction Factors
- Single-relation plans
- Multi-relation plans
- Motivation for Normalisation
- Functional dependency
  - Armstrong’s Axioms
- Steps in Normalisation
- Normalisation vs Denormalisation
- Capacity Planning
  - Transaction load
  - Storage requirements
- Backup and Recovery
  - Motivation
  - Failure
- Backup Taxonomy
  - Physical vs Logical
  - Online vs Offline Backup
  - Full vs Incremental Backup
  - Onsite vs Offsite Backup
- Backup Policy
- Transactions
  - Defining a unit of work
  - ACID: Transaction properties
- Concurrent Access
  - Serialisability
  - Concurrency Control Methods

  - Locking
  - Lock Granularity
  - Lock types
  - Deadlock
  - Timestamping
  - Optimistic
- Transaction Log
- Data Warehousing
  - Motivation
  - Analytical Queries
  - DW Characteristics
- Dimensional Modelling
  - Dimensional model
  - Designing a dimensional model
  - Embedded Hierarchies
  - Snowflake schema
  - Denormalisation
- Distributed Databases
  - Advantages
  - Disadvantages
  - Objectives and Trade-offs
- Distribution Options
  - Data Replication
  - Synchronous Update
  - Asynchronous Update
  - Horizontal Paritioning
  - Vertical partitioning
- Comparing configurations
- Functions of a distributed DBMS
- Date’s 12 Commandments for Distributed Databases
  - Independence
  - Transparency
- Motivation for NoSQL

- NoSQL Goals
- Object-relational impedance mismatch
- 3Vs of Big Data
- Big Data Characterisitics
- NoSQL Features
- NoSQL Variants - Aggregate oriented
  - Key-value stores
  - Document database
  - Column family
- NoSQL Variants - Graph databases
- CAP Theorem
- ACID vs BASE

1. Databases

Data vs Information

- **Data**: known facts, stored and recorded e.g. text, numbers, dates, …
- **Information**:
  - data presented in context.
  - may be summarised/processed.
  - increases user knowledge.
- Data is known and available; information is processed and more useful
- **DBMS**: software designed to store, manage, facilitate access to databases

File processing systems vs databases

File processing systems

- data duplication: wasteful
- program-data dependence: program needs to change if file structure changes
- poor data sharing
- high program maintenance
- long development time

Database systems

- data independence: separate data from program
- minimise data redundancy
- improve data consistency
- improve data sharing
- reduce program maintenance
- ad hoc data access via SQL

2. Database development lifecycle

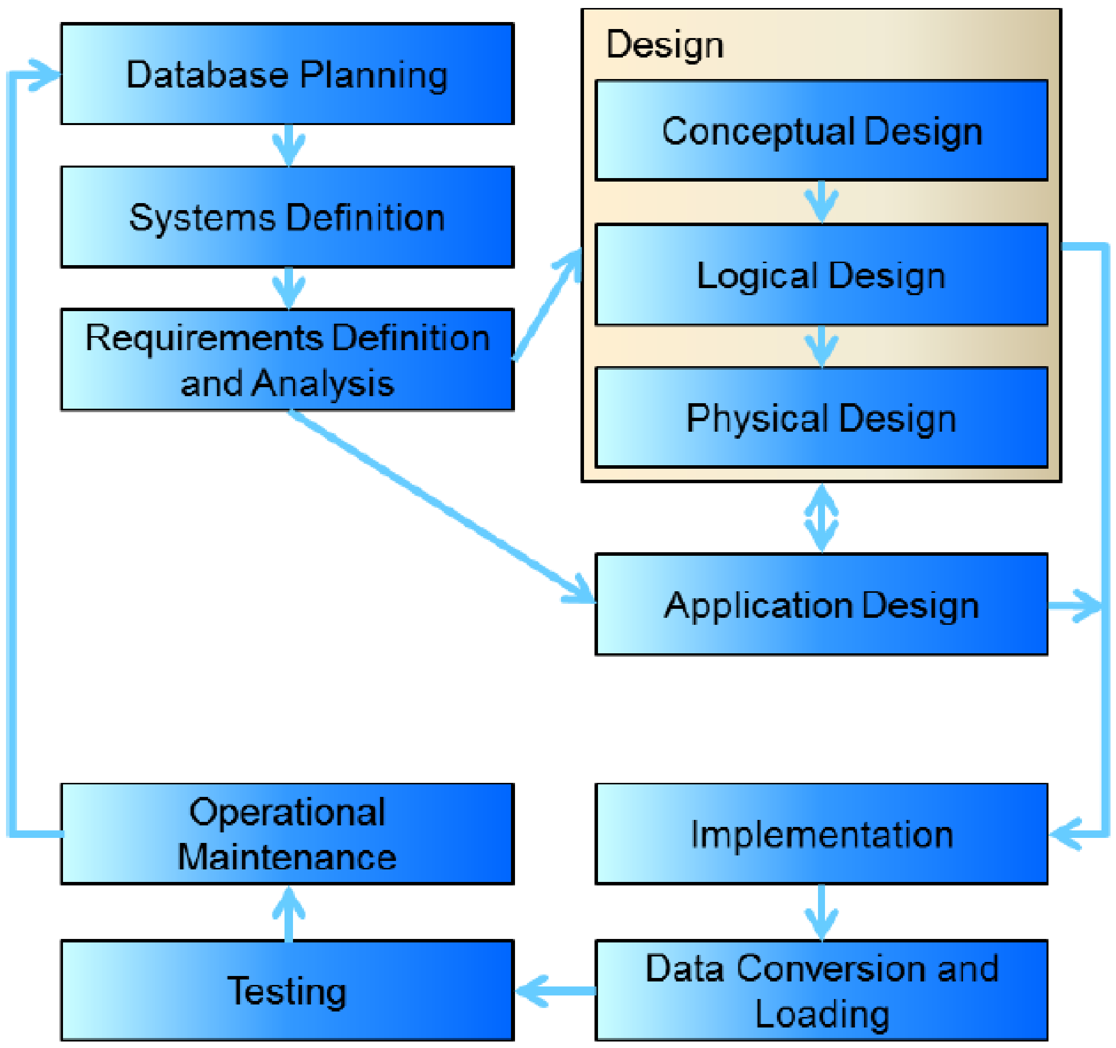


Figure 1: database development lifecycle

- Planning: how to do project
  - how enterprise works; top level perspective on data requirements
  - enterprise data model
- Systems definition: specify scope and system boundaries
  - who are the users, what is the application area
  - how does system interfere/interact with other systems

- Requirements definition and analysis: collection and analysis of requirements for the new system
- Conceptual design: construct model of data independent of physical considerations
  - Identify business rules
  - ER entity-relationship diagrams
- Logical design
  - relational model of data based on conceptual design
  - independent of specific database
  - foreign keys
  - cardinality
- Physical design: description of implementation of logical design for a specific DBMS
  - data types: help ensure consistency, integrity, minimise storage space
    - need to consider range of possible values and data manipulation required
  - file organisation
  - indexes
  - look up/go between tables
  - whether or not to perform normalisation/de-normalisation
    - denormalise: improved performance; increased storage requirements; may reduce data integrity/consistency
- Application design
  - design of interface and application
  - programs that use/process database
- Implementation
  - physical realisation of database
- Data conversion and loading
  - transfer existing data into database
  - conversion from old systems
  - non-trivial
- Testing
  - run database to find errors in design/setup
  - assess performance, robustness, recoverability, adaptability

- Operational maintenance
    - monitoring and maintaining the database
    - handling new and changed requirements

3. Conceptual Design

Entities and relationships

- **entity**: real-world object distinguishable from other objects, described by a set of attributes
- **entity set**: collection of entities of the same type. All entities in an entity set have the same set of attributes, and is identified by a key.
- **relationship**: association between two or more entities
    - can have attributes
- **relationship set**: collection of relationships of the same type

Constraints

- **key constraints**: number of objects participating in the relationship set
    - upper bound
    - e.g. an employee can work in *many* departments, a department can have *many* employees
    - one-to-many: represented by an arrow towards relationship set
- **participation constraint**: whether all entities in a relationship participate in a relationship
    - lower bound
    - **total participation**: all entities must participate; bold line
    - **partial participation**: not every entity need participate

Weak Entity

- **weak entity**: uniquely identified by considering primary key of owner entity
    - represented by bold rectangle
    - identifying relationship also bold
    - total participation in identifying relationship
    - only have a partial key (dashed underline)

Ternary relationships

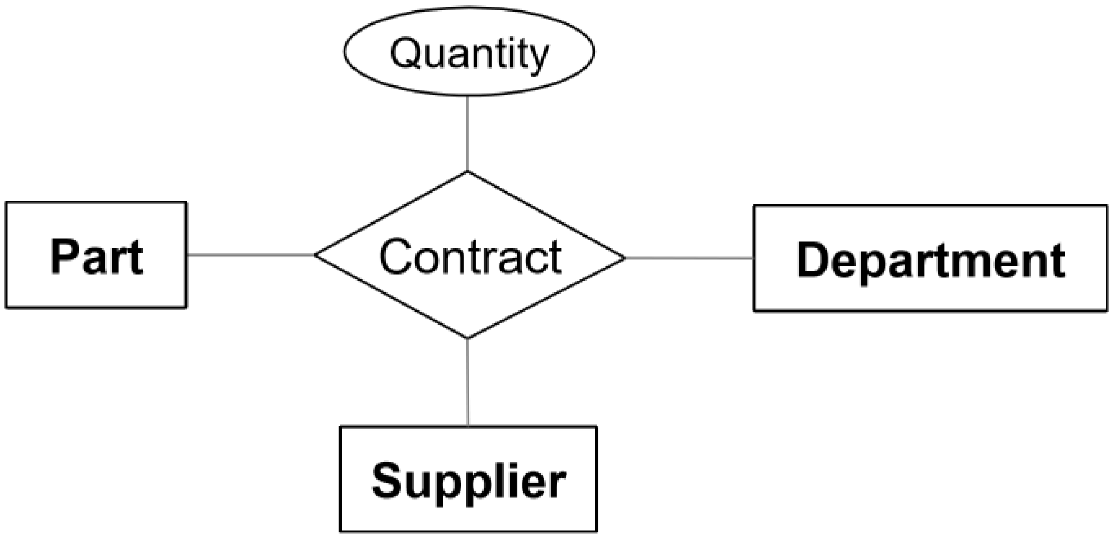


Figure 2: ternary-relationship

Attributes

- **multi-valued attributes**: multiple values of same type (e.g. phone numbers)
- **composite attributes**: structured values of possibly different type e.g. address
- entity vs attribute: depends on how you use information e.g. several addresses per employee, you should model address as an entity

4. Translating ER diagrams

Relational Data Model

- **data model**: allows you to translate real world things into form that can be stored by a computer
  - relational, ER, object-oriented, …
- **relational model**:
  - rows: aka tuples, records
  - columns: aka attributes, fields

- **relational database**: set of relations
- **relation**: schema + instance
  - **schema**: specifies name of realtion, name and type of each column
  - **instance**: table with rows and columns
    - **cardinality**: number of rows
    - **degree**: number of fields
  - relation is a set of distinct, unordered rows

Keys

- **keys**: associate tuples in different relations
  - form of **integrity constraint**: e.g. only students can be enrolled in subjects

Primary key

- **superkey**: set of fields where no two distinct tuples have the same values for all fields
- set of fields is a **key** for a relation if:
  - it is a superkey, and
  - no subset of fields is a super key, i.e. it is a minimal subset
- **primary key**: chosen key for the relation
- **candidate key**: all other keys
- each relation has a primary key

Foreign key

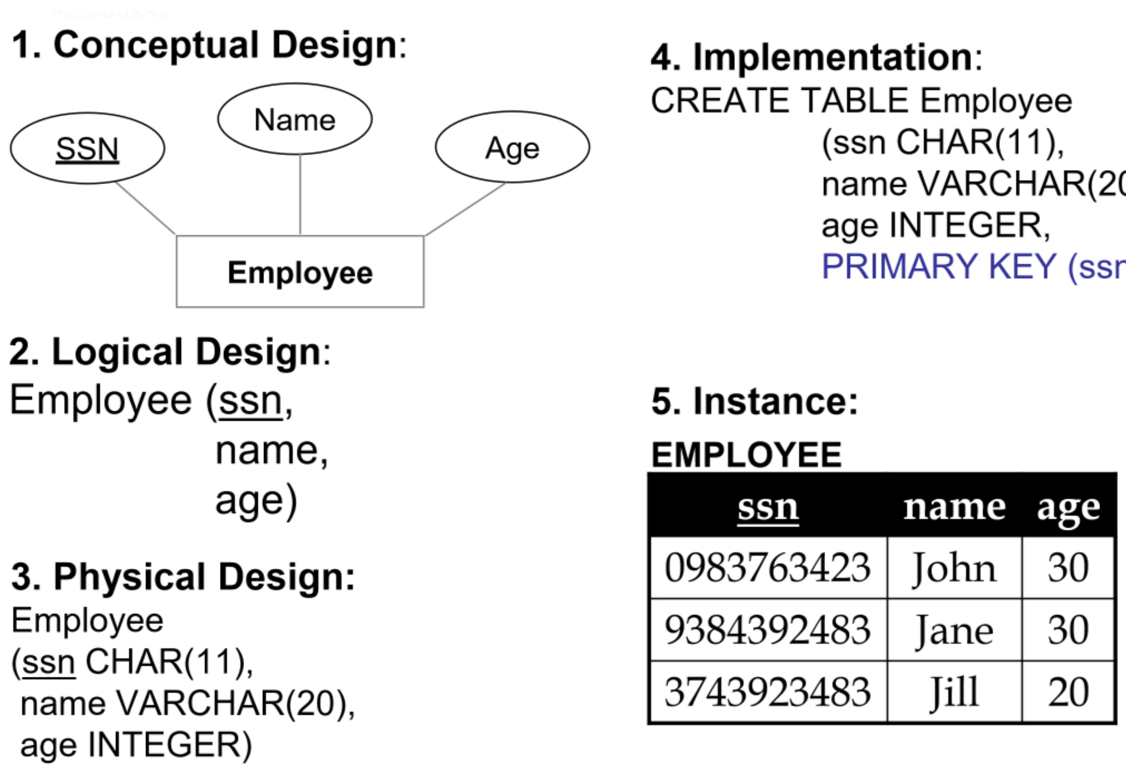
- **foreign key**: set of fields in one relation used to refer to a tuple in another relation. Must correspond to primary key in the other relation
- **referential integrity**: achieved when all foreign key constraints are enforced

Integrity constraints

- **integrity constraint/IC**: condition that must be true for any instance of the database
  - specified when schema is defined
  - checked when relations are modified
  - instance of a relation is **legal** if it satisfies all specified ICs

ER to Relational model

- logical design:
  - entity sets become relations
  - attributes become attributes of relation
- physical design: assign data types



1. Conceptual Design:

2. Logical Design:
Employee (ssn,
name,
age)

3. Physical Design:
Employee
(ssn CHAR(11),
name VARCHAR(20),
age INTEGER)

4. Implementation:

```
CREATE TABLE Employee
        (ssn CHAR(11),
        name VARCHAR(20),
        age INTEGER,
        PRIMARY KEY (ssn))
```

5. Instance:

EMPLOYEE

ssn	name	age
0983763423	John	30
9384392483	Jane	30
3743923483	Jill	20

Figure 3: db-design-cycle

- multi-valued attributes: either flatten or introduce lookup table

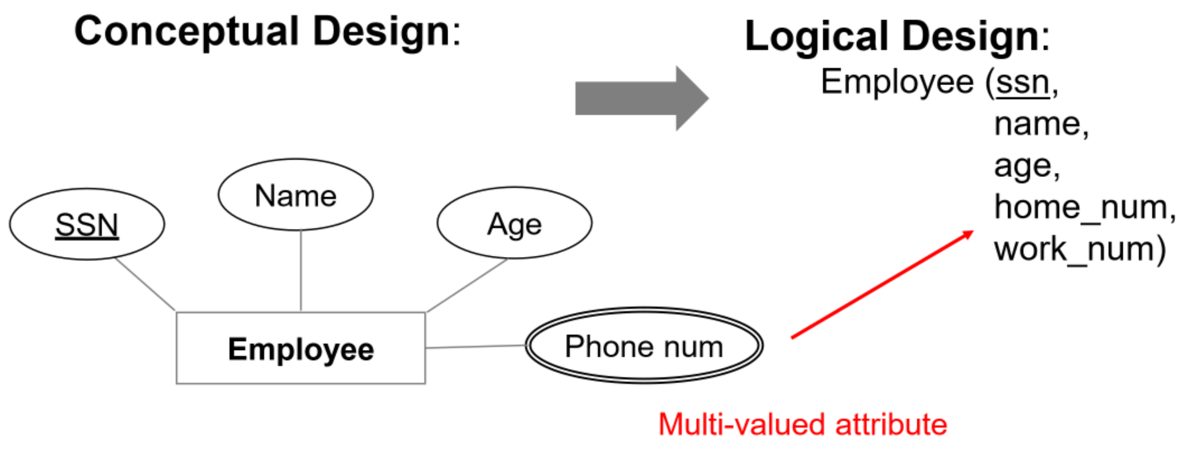
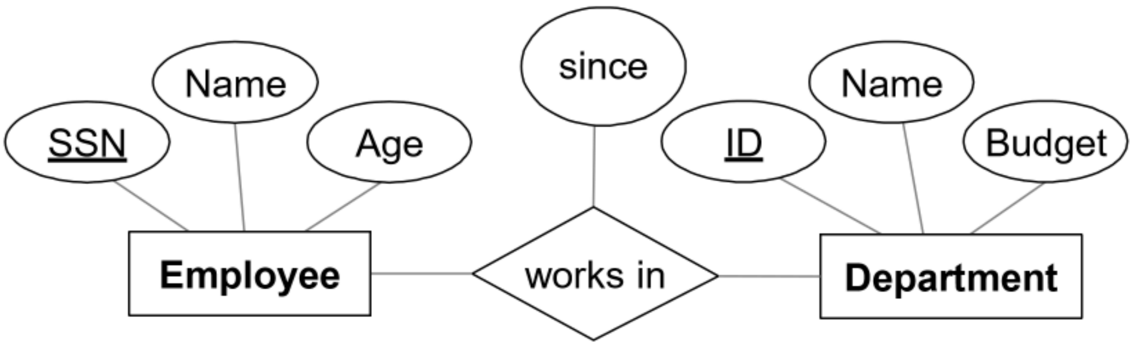


Figure 4: multi-valued-attribute

- composite attributes: flatten
- many-to-many relationship set to relation
    - include keys for each entity set as foreign keys. This will form a superkey
    - descriptive attributes

Example



Conceptual design

Logical design

```
Employee(ssn PK, name, age)
Department(did PK, dname, budget)
Works_In(ssn PFK, did PFK, since)
```

Physical Design

```
Employee(ssn CHAR(11) PK,
         name VARCHAR(20),
         age INTEGER)
```

```
Department(did INTEGER PK,
           dname VARCHAR(20),
           budget DECIMAL(10, 2))
Works_In(ssn CHAR(11) PFK,
         did INTEGER PFK,
         since DATE)
```

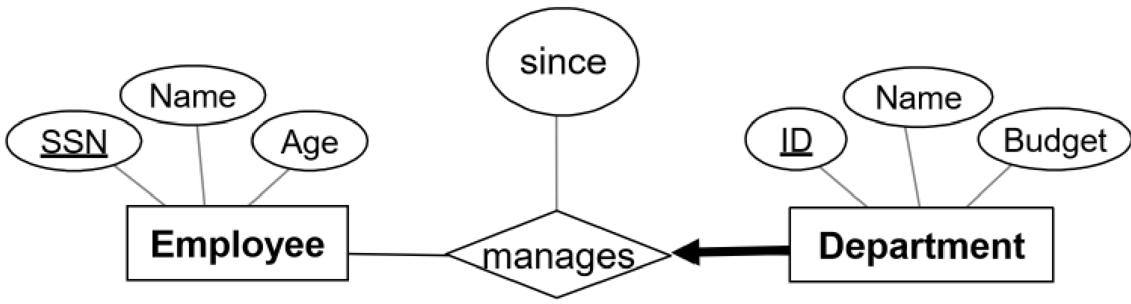
Implementation

```
CREATE TABLE Employee (
    ssn CHAR(11),
    name VARCHAR(20),
    age INTEGER,
    PRIMARY KEY (ssn)
);

CREATE TABLE Department (
    did INTEGER,
    dname VARCHAR(20),
    budget DECIMAL(10, 2),
    PRIMARY KEY (did)
);

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

Example: key and participation constraints



Conceptual model

- each department has at most one manager

- **rule: primary key from many side becomes foreign key on the one side**
  - this ensures the key constraint holds
- every department has a manager: total participation. Enforce with `NOT NULL`

Implementation

```
CREATE TABLE Department (
    did INTEGER,
    dname VARCHAR,
    budget DECIMAL(10, 2),
    since DATE,
    ssn CHAR(11) NOT NULL,
    PRIMARY KEY (did),
    FOREIGN KEY (ssn) REFERENCES Employee
        ON DELETE NO ACTION
);
```

Example: Weak Entity

- weak entity set and identifying relationship set become a single table
- when owner is deleted, all owned weak entities must also be deleted

Logical design

```
Dependent(dname PK, age, cost, ssn PFK)
```

Implementation

```
CREATE TABLE Dependent (
    dname CHAR(20) NOT NULL,
    age INTEGER NULL,
    cost DECIMAL(7, 2) NOT NULL,
    ssn CHAR(11) NOT NULL,
    PRIMARY KEY (dname, ssn),
    FOREIGN KEY (ssn) REFERENCES Employee
        ON DELETE CASCADE
);
```

5. MySQL Workbench

- **derived attributes**: values can be derived from other attributes in the database
  - need not be stored physically: redundant, threat to integrity

  - may want to store so that you don't have to recompute
  - e.g. number of years employee has been employed

Conceptual to logical checklist

1. Flatten composite and multi-valued attributes, or introduce lookup table for multi-valued attributes when number of values is unknown or variable.
2. Resolve many-many relationships
3. Add foreign keys at crows foot end of relationship (many side)

Convert from Logical

- choose data types
- choose whether `NULL` or `NOT NULL`

Binary relationships

- **one-to-many**: primary key on one side becomes foreign key on many side
- **many-to-many**: create associative entity (new relation) with primary key of each entity as combined primary key
- **binary one-one relationship**: primary key on mandatory side becomes foreign key on optional side
  - otherwise just choose one

Unary relationships

- **one-to-one**: put FK in relation
- **one-to-many**: put FK in relation
- **many-to-many**: generate associative entity
  - put two foreign keys in it

Ternary relationship

- generate associative entity
- 3 one-to-many relationships: add FKs

6. Relational Algebra

Basic Operations

- **Selection** σ: select subset of rows satisfying selection condition
  - result: relation with identical schema to input relation
- **Projection** π: retain wanted columns in projection list
  - schema: contains only fields in projection list
  - eliminates duplicates
- **Set-difference** $-$: get tuples in one relation but not the other
  - input relations must be union-compatible
  - not symmetrical: $S1 - S2 \neq S2 - S1$
- **Union** $\cup$: tuples in one relation and/or in the other
  - input relations must be union-compatible
  - duplicates removed
- **Cross product** $\times$: combine two relations
  - each row of one input merged with each row from another input
  - output: new relation with all attributes of both inputs
  - e.g. num tuples of $S \times R = card(S).card(R)$
- **renaming operator** ρ: useful for naming conflicts e.g. in cross product
  - $\rho(ResultName(\text{ field1 } \rightarrow \text{newField1, field2} \rightarrow \text{newField2}), S \times R)$
- **union-compatible**:
  - same number of fields
  - corresponding fields are of the same type
- **or**: $\vee$
- **and**: $\wedge$

Compound Operators

- no additional computational power: they can be expressed in terms of basic operations
- may be useful shorthand

- **intersection** $\cap$: retain rows appearing in both relations
  - inputs must be union-compatible
  - $R \cap S = R - (R - S)$
- **join**: cross product + selection + optional projection
- **natural join** $R \bowtie S$: match rows where attributes appearing in both relations have equal values. Omit duplicate attributes. Steps:
  - compute $R \times S$
  - select rows where attributes in both relations have equal values
  - project all unique attributes, copy each common one
- **condition join/theta join** $R \bowtie_c S = \sigma_c(R \times S)$: cross product with a condition
- **equi-join**: special case of condition join, where condition only contains equalities

8, 9. SQL

SQL

- Structured Query Language
- Supports CRUD commands:
  - Create
  - Read
  - Update
  - Delete
- capabilities:
  - **data definition language DDL**: define, set up database
    * `CREATE`, `ALTER`, `DROP`
  - **data manipulation language DML**: maintain, use database
    * `SELECT`, `INSERT`, `DELETE`, `UPDATE`
  - **data control language DCL**: control access to the database
    * `GRANT`, `REVOKE`
  - administration
  - transactions

`SELECT` statement overview

```
# List columns/expressions returned from query
SELECT [ALL|DISTINCT] select_expr [, select_expr ...]
# tables from which data is obtained
FROM table_references
# filtering conditions
WHERE where_condition
# categorisation of results
GROUP BY { col_name | expr } [ASC | DESC], ...
# filtering conditions for categories.  Can only be used with a GROUP
    BY
HAVING where_condition
# sort
ORDER BY {col_name | expr | position} [ASC | DESC]
# limit which rows are returned
LIMIT {[offset, ] row_count | row_count OFFSET offset}];
```

`LIKE` Clause

- %: 0+ characters
- '_': exactly 1 character

```
LIKE "<regex>"
```

e.g.

```
SELECT * FROM Customer
# any values starting with "a"
WHERE CustomerName LIKE 'a%'
# any values starting with "a", at least 3 values long
WHERE CustomerName LIKE 'a_%_%'
# any values starting with "a", ends with "o"
WHERE CustomerName LIKE 'a%o'
```

Aggregate Functions

MySQL Group By Functions

- `AVG()`
- `MIN()`
- `MAX()`
- `COUNT()`: counts number of records
- `SUM()`

- all except COUNT ignore null values and return null if all values are null

Order By

```
ORDER BY XXX ASC/DESC
```

Joins

- Cross product: not usually useful. Typically want records matching on a key

```
# Cross product
SELECT * FROM R1, R2;

# Natural join: join tables on keys.  Attributes must have same name
SELECT *
FROM R1 NATURAL JOIN R2;

# Inner join: only retain matching rows
SELECT *
FROM R1 INNER JOIN R2
    ON R1.id = R2.id;
k
# Outer join:: left/right; includes records that don't match from the
   outer table
SELECT *
FROM R1 LEFT OUTER JOIN R2
    ON R1.id = R2.id;
```

Comparison and logical operators

- <>, !=: not equal to
- IN, NOT IN: test whether attribute is in/not in subquery list
- ANY: true if any value meets condition
- ALL: true if all values meet condition
- EXISTS: true if subquery returns 1+ record

Set operators

- MySQL specific
- UNION: classical set operation, no duplicates
- UNION ALL: duplicates allowed

Other Statements

`INSERT` Statement

- insert records into a table

```
# insert single record
INSERT INTO NewEmployee SELECT * FROM Employee;

# insert multiple records
INSERT INTO Employee VALUES
    (DEFAULT, "A", "address A", "2012-02-12", NULL, "S"),
    (DEFAULT, "B", "address B", "2012-02-12", NULL, "R");

# insert specific columns
INSERT INTO Employee
    (Name, Address, DateHired, EmployeeType)
    VALUES
        ("D", "address D", "2012-02-12", "C"),
        ("E", "address E", "2012-02-12", "C");
```

`UPDATE`

- change existing data in table

```
UPDATE Salaried
    SET AnnualSalary =
        CASE
            WHEN AnnualSalary <= 100000
            THEN AnnualSalary * 1.1
            ELSE AnnualSalary * 1.05
        END;
```

`REPLACE`

- works identically to insert, but row is updated if it exists, otherwise a new row is inserted

`DELETE`

- dangerous!
- in production, you don't physically delete, you use a flag to indicate not active, known as a logical delete

```sql
DELETE FROM Employee
    WHERE Name = "Grace";
```

- foreign key constraints
  - `ON DELETE CASCADE`
  - `ON DELETE RESTRICT`: prevent deletion if child row exists

Views

- **view**: relation not in physical model, but made available to end user as a virtual relation
- hides query complexity from user
- hides data from users: helps improve DB security
- once created, schema is stored in DB, and it can be used like any other table

```sql
CREATE VIEW nameOfView AS validSqlStatement
```

More DDL

`ALTER`

- allows you to add/remove attributes from a table

```sql
ALTER TABLE TableName ADD AttributeName AttributeType;
ALTER TABLE TABLENAME DROP AttributeName;
```

`RENAME`

- allows you to rename table

```sql
RENAME TABLE CurrentName TO NewName;
```

Approach for writing SQL

1. Use design as a map to help format queries
2. Create skeleton `SELECT` statement as a template
3. Fill in parts to build query

10. Storage and Indexing

Files in DBMS

- **file**: collection of pages, each containing collection of records
  - each record has a record ID, correspoding to physical address of page that the record is on
- DBMS must support:
  - insert, delete, modify records
  - read particular records
  - scan all records
- pages are stored on hard disks HDD
- for processing, pages need to be loaded into RAM
- costs of operations modelled by DBMS in terms of number of page accesses (disk I/Os)
- **heap files**: no order among records
  - suitable for retrieval of all records
  - as file grows/shrinks pages are allocated/deallocated
  - fastest for inserts
- **sorted file**: pages and records ordered by some condition
  - fast for range queries
  - hard to maintain: each insertion may reshuffle records
  - rarely done in practice; B+ tree index is a better option
- **index file organisation**: fastest retrieval in some order
  - best tool a DBA has to optimise a query

Indexes

- **index**: data structure built on top of data pages used for efficient search
  - built over **search key fields**: selections on search key fields will be fast
    - any subset of fields of a relation can be search key for an index
    - search key is distinct from key, and need not be unique

- contains collection of **data entries**, supporting efficient retrieval of **data records** matching a given **search condition**

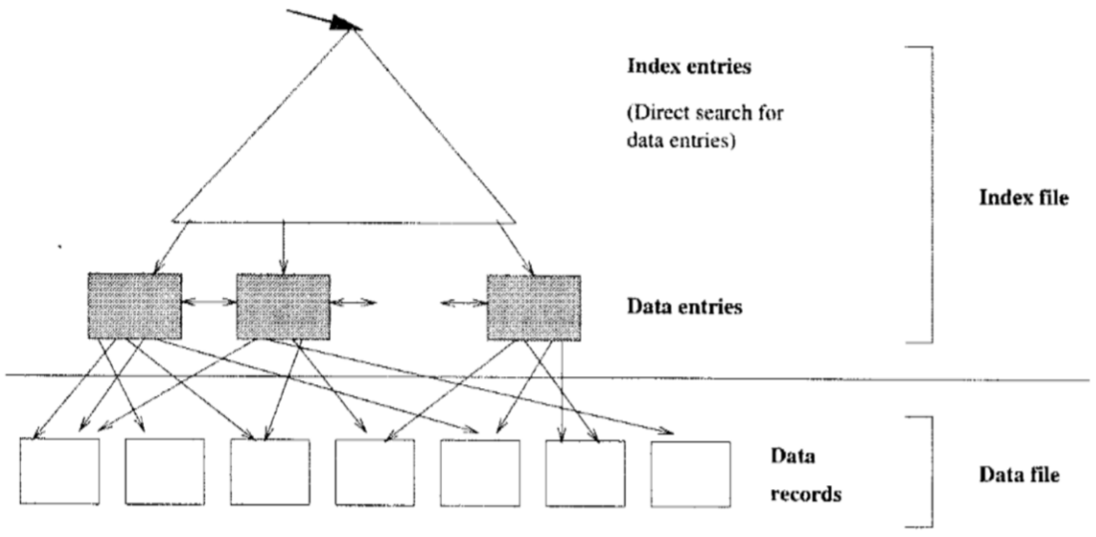


Figure 5: unclustered-index

Clustered vs Unclustered

- **clustered**: order of data records is the *same* as order of index data entries
  - e.g. if the underlying file is sorted on the same fields
  - you cannot have multiple clustered indexes over a single table
  - much cheaper for clustered retrieval
  - more expensive to maintain
  - very efficient for range search
  - Cost ~ number of pages in data file with matching records

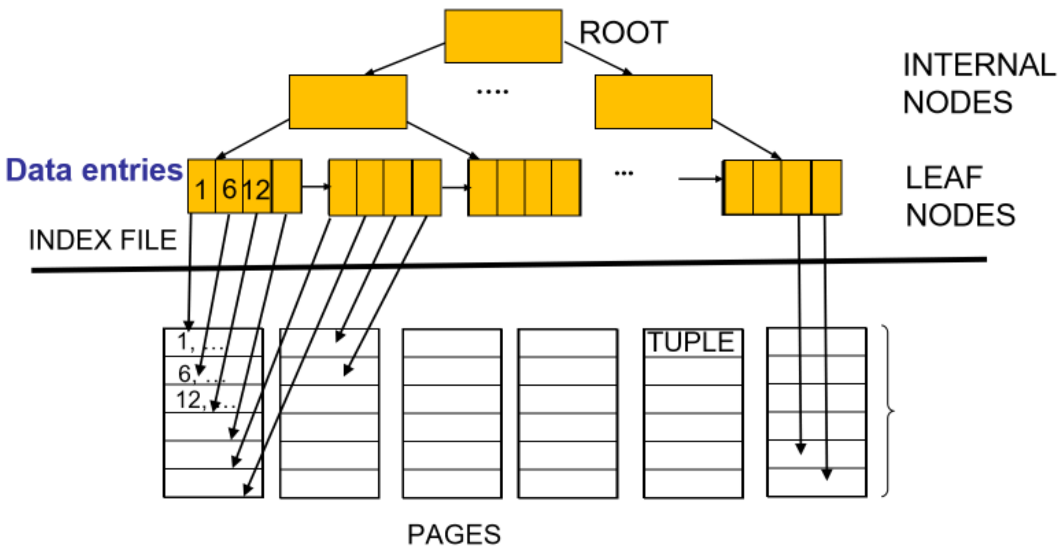


Figure 6: clustered-index-zoom

- **unclustered**: order of data records is *different* from order of index data entries
  - e.g. heap file
  - cost ~ number of matching index data entries (data records)

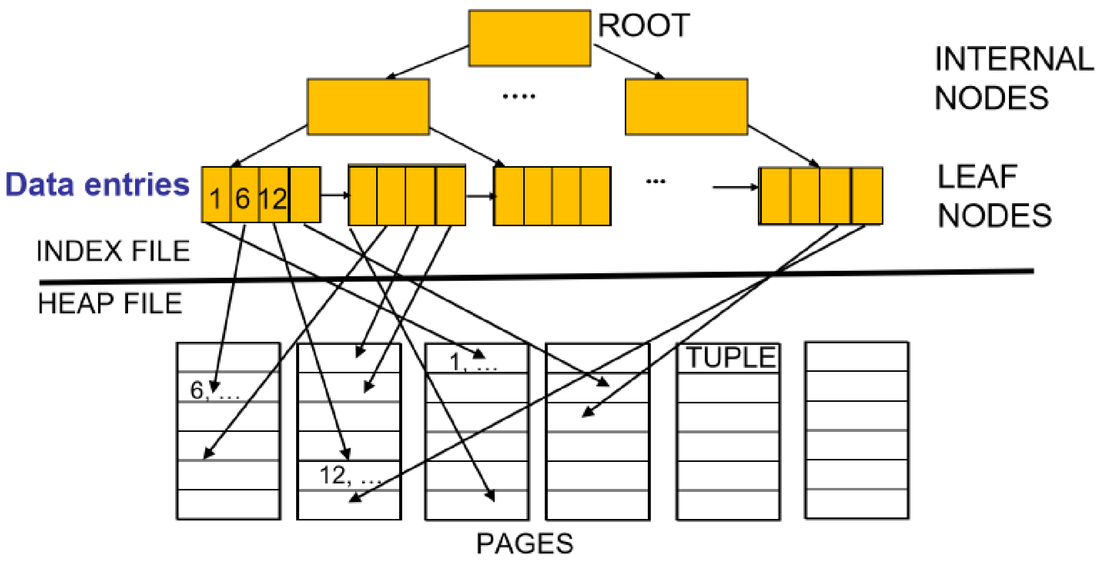


Figure 7: unclustered-index-zoom

Primary vs Secondary

- **primary index** includes table's primary key
  - never contains duplicates
- **secondary index** is any other index
  - may contain duplicates

Single Key vs Composite Key

- index can be built over a combination of search keys
- data entries in the index are sorted by search keys

Index Type

- **hash-based index**: index is a collection of buckets
  - hash function maps search key to corresponding bucket

- h(r.search_key) = bucket in which record r belongs
- good for **equality** selections
- bad for range selections

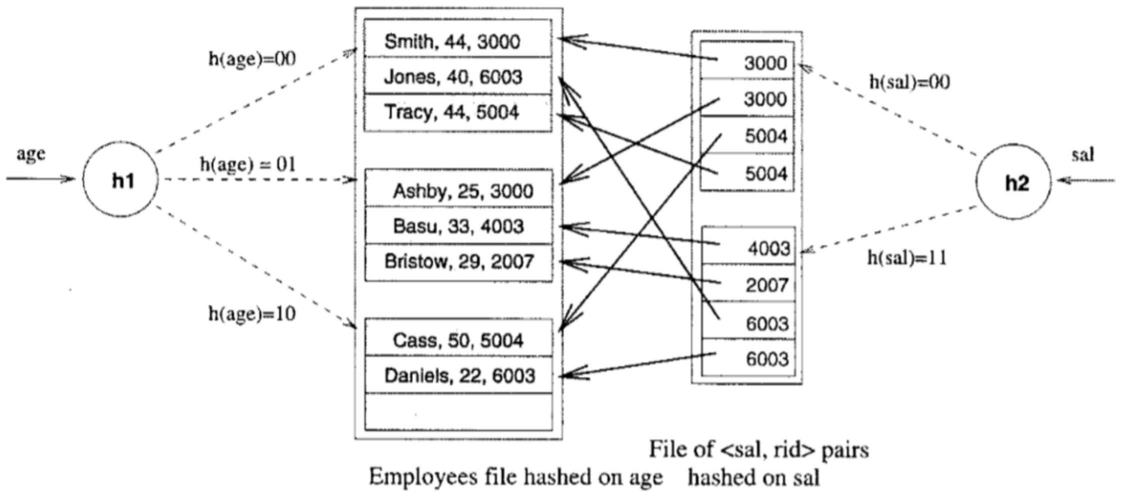


Figure 8.2 Index-Organized File Hashed on *age*, with Auxiliary Index on *sal*

Figure 8: hash-based-index

- **tree-based index**: B+ tree
  - nodes contain pointers to lower levels
  - leaves contain data entries
  - B+ tree maintains a short path from root to leaf, minimising I/Os
  - good for range selections

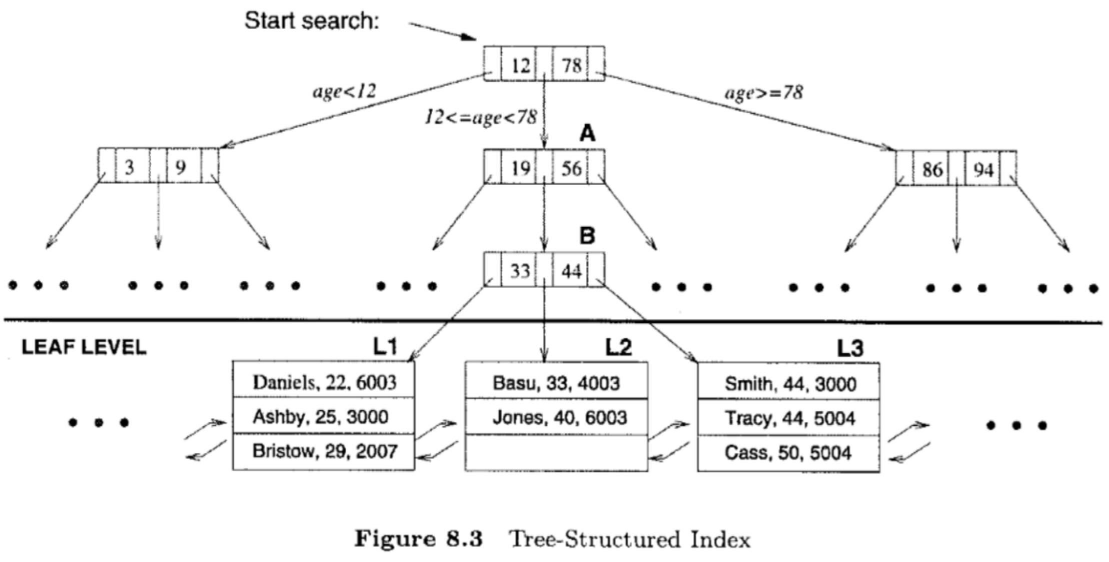


Figure 9: tree-based-index

- choosing an index depends on the needs of the database: if selection queries are frequent, building an index is important. The type of index you choose will depend on the type of queries that are performed

11. Query Processing

Query Processing

- some DB operations are expensive
- clever implementation can result in 10^6 performance improvement
- tools:
  - clever implementation techniques for operators
  - exploit equivalencies of relational operators
  - use cost models to choose between alternatives

Relational Operations

Selection

- multiple predicates:

- a B+ tree index matches predicates that involve attributes in a **prefix of the search key**.
- e.g. Index on `<a,b,c>`:
  - matches predicates on `(a,b,c), (a, b)` and `(a)`
  - matches `a = 5 AND b = 3`
  - does not match `b = 3`
  - only **matching predicates** are used to determine cost
- e.g. index on `<a, b>`: Can this be used to estimate cost of following conditions?
  - `a > x`: yes
  - `a > x AND b > y`: yes
  - `b > y`: no
  - `a = 5 AND b = 3 & c = 7`: yes. Only the first two are matching predicates.
- approach:
  - find **cheapest access path**: index/file scan with lowest estimated page I/O
  - retrieve tuples using it: predicates that match the index reduce the number of tuples retrieve, and impact the cost
  - apply predicates that don't match the index later on, **on-the-fly**, in memory
    * doesn't affect total number of tuples/pages fetched

Projection

- issue: removing duplicates is expensive
- approaches: hashing, sorting
- sorting:
  - scan whole relation, extract only needed attributes
  - sort the result set (external merge sort)
  - remove adjacent duplicates

External Merge Sort

- used when data doesn't fit in memory all at once
- conduct several passes:
  - sort runs: make each of B pages individually sorted (runs)
  - merge runs: make multiple passes to merge runs

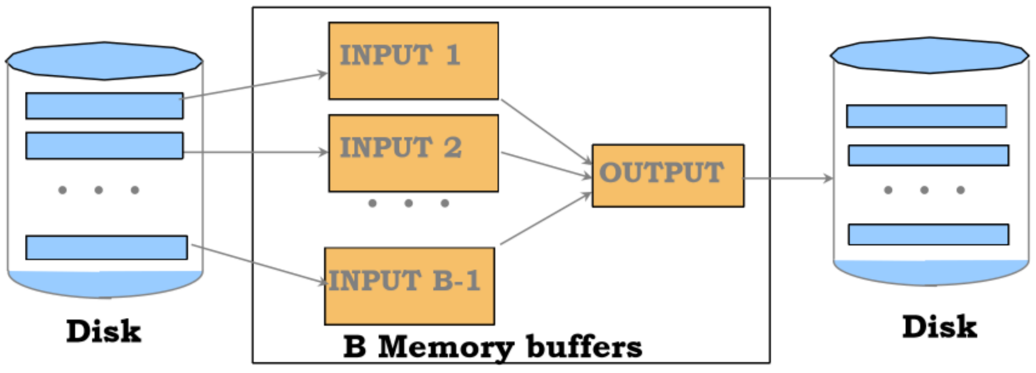


Figure 10: external-merge-sort

Sort-based Projection

```
Cost =  ReadTable +                # read entire table, keep projected
    attributes
        WriteProjectedPages +      # write back to disk
        SortingCost +              # external merge sort
        ReadProjectedPages         # discard adjacent duplicates

WriteProjectedPages = NPages(R) * PF
SortingCost = 2*NumPasses*ReadProjectedPages
```

- **projection factor PF**: how much we are projecting, ratio with respect to all attributes
  - e.g. keeping 10% of all attributes

Hash-based projection

- scan R, extract needed attributes
- hash data into buckets: apply hash function `h1` to choose one of `B` output buffers
- remove adjacent duplicates from a bucket
  - 2 tuples from different partitions guaranteed to be distinct

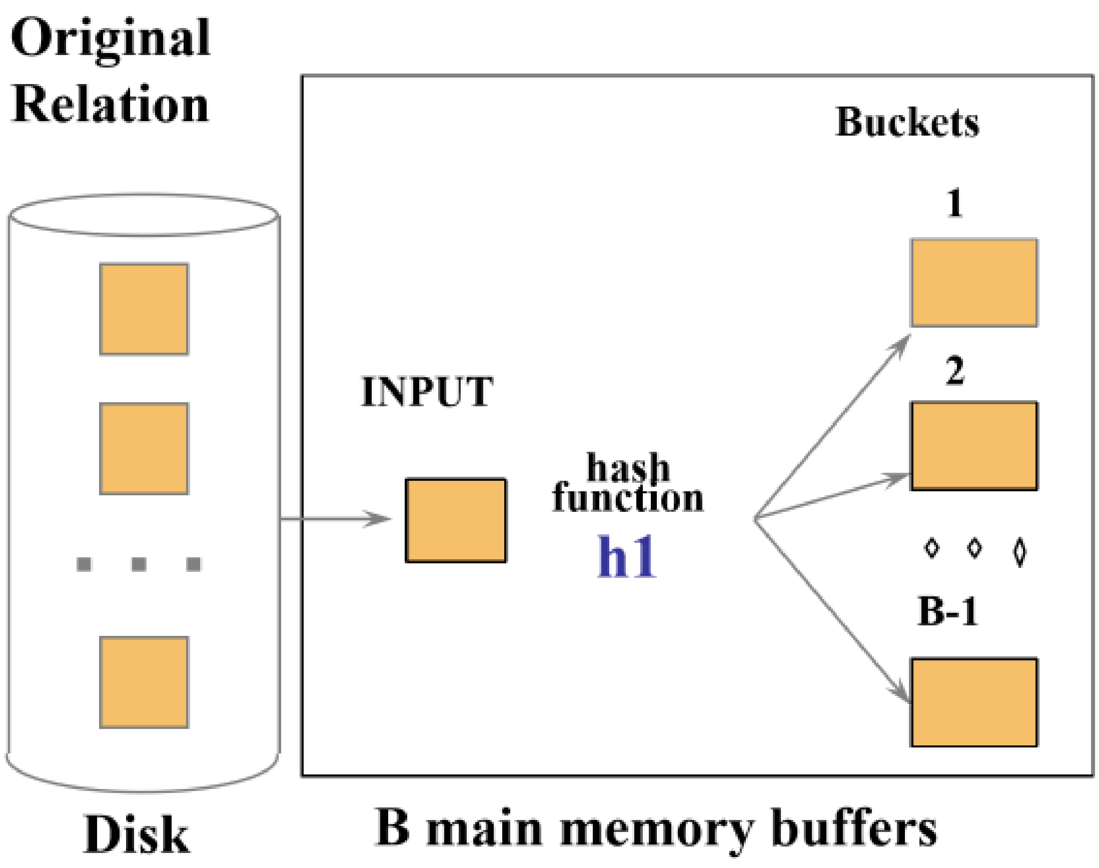


Figure 11: projection-hashing

- external hashing
  - partition data into B-1 partitions with hash function `h1`
  - load each partition, hash it with a different hash function `h2` and eliminate duplicates

```
Cost = ReadTable + WriteProjectedPages + ReadProjectedPages
```

12. Query Processing II

Joins

- very common
- can be very expensive (cross product in worst case)

- in expression $R \times S$:
  - R: left/outer
  - S: right/inner
- properties
  - commutative: $A \times B = B \times A$
  - associative: $A \times (B \times C) = (A \times B) \times C$

Simple nested loop join

- $R \bowtie S$
- for each tuple in outer relation R, we scan entire inner relation S

```
for each tuple r in R:
  for each tuple s in S:
    if ri = sj:
       add <r, s> to the result
```

```
Cost(SNLJ) = NPages(Outer) + NTuples(Outer) * NPages(Inner)
```

Page-Oriented Nested Loop Join

- $R \bowtie S$
- for each page of R, get each page of S.
  - Write out matching pairs of tuple `<r, s>`

```
for each page b_r in R:
  for each page b_s in S:
    for each tuple r in b_r:
      for each tuple s in b_s:
        if r_i = s_j, add <r,s> to the result
```

```
Cost(PNLJ) = NPages(Outer) + NPages(Outer) * NPages(Inner)
```

Block Nested Loop Join

- exploit additional memory buffers
- use one page as input buffer for scanning inner S
- use one page as output buffer

- use all remaining pages to hold block of outer R

```
for each block in R:
  for each page in S:
    for each matching tuple r in R-block, s in S-page:
      add `<r, s>` to result
```

$$\text{NBlocks(Outer)} = \lceil \frac{\text{NPages(Outer)}}{B-2} \rceil$$

```
Cost(BNLJ) = NPages(Outer) + NBlocks(Outer)*NPages(Inner)
```

Sort-Merge Join

- sort R and S on the join column
- scan them to do a merge
- output result tuples
- useful when:
  - one/both inputs are already sorted on join attributes
  - output required to be sorted on join attributes

```
Cost(SMJ) = Sort(Outer) + Sort(Inner)      # Sort inputs
          + NPages(Outer) + NPages(Inner) # Merge inputs

Sort(R) = external sort cost = 2*NumPasses*NPages(R)
```

Hash Join

- partition both relations using hash function `h`: tuples from R in partition 1 can only match tuples from S in partition 1
- read in a partition of R, hash with a different hash function `h2`
  - scan matching partition of S and probe the hash table for matches

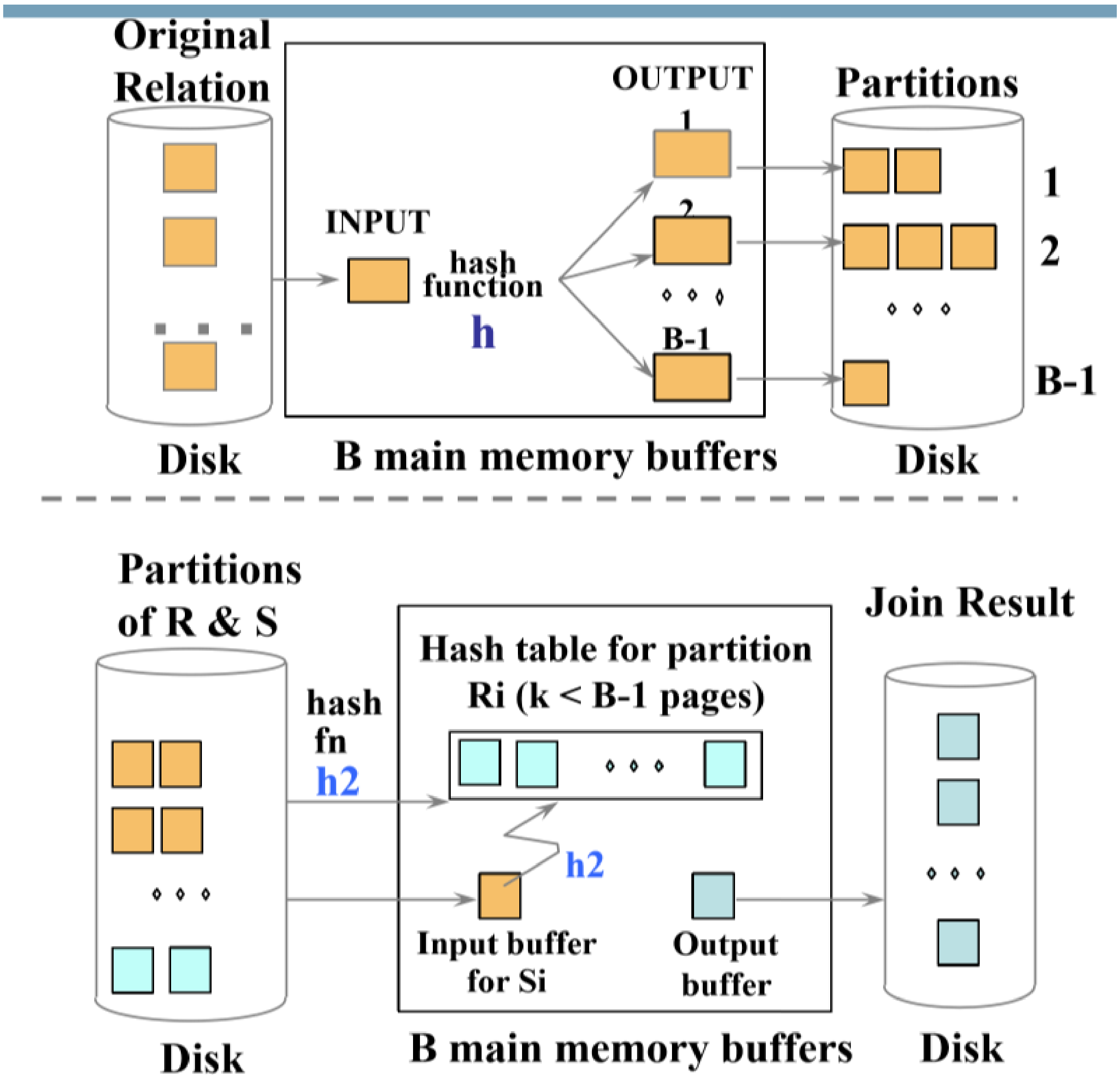


Figure 12: hash-join

```
Cost(HJ) = 2*NPages(Outer) + 2*NPages(Inner)  # Create partitions
           + NPages(Outer) + NPages(Inner)    # Match partitions
```

General Joins

- equality over several attributes
  - for sort-merge and hash join, sort/partition on combination of the join columns

- range/inequality conditions
  - hash join, sort merge join not applicable
  - block NL likely to be best join method here

13. Query Optimisation

Query plan

- tree with relational algebra operators as nodes
- pipeline of tuples from bottom to top
- exclude cost of writing result, as this will be identical for all plans
- each operator labeled with choice of algorithm

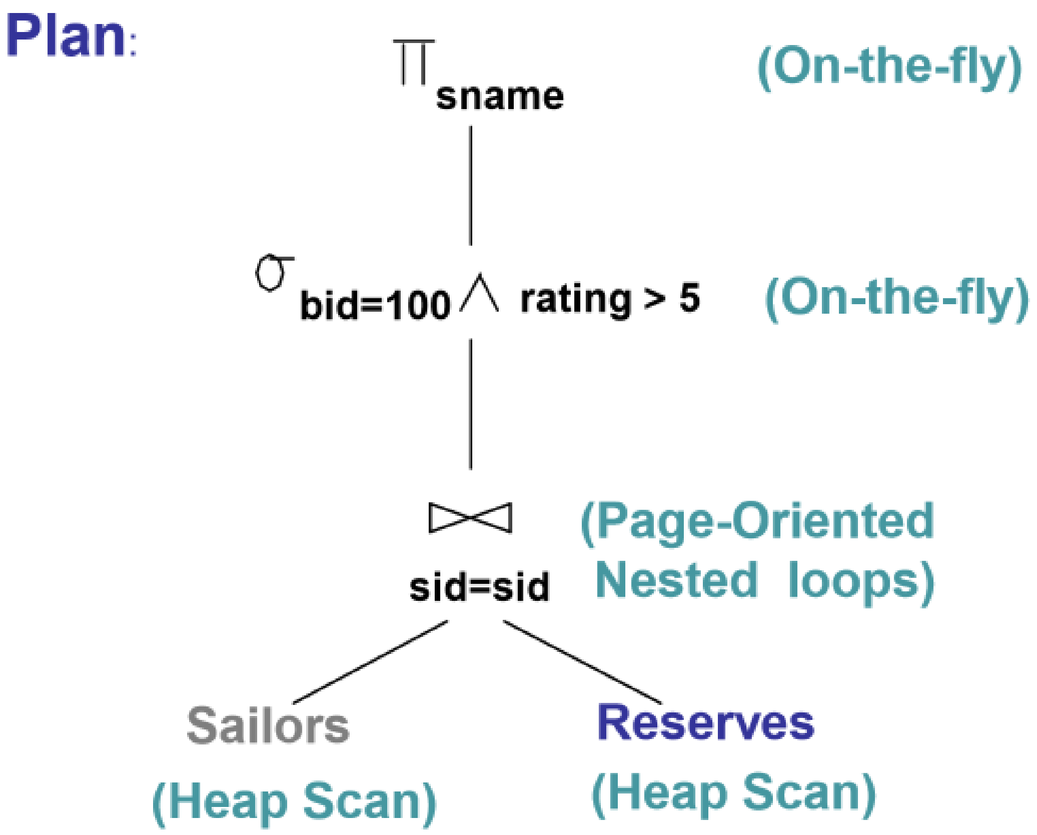

Plan:
π_{sname}
(On-the-fly)
$\sigma_{\text{bid}=100 \wedge \text{rating} > 5}$
(On-the-fly)
$\bowtie_{\text{sid}=\text{sid}}$
(Page-Oriented Nested loops)
Sailors
(Heap Scan)
Reserves
(Heap Scan)

Figure 13: query-plan

Query optimisation steps

1. break query into blocks
2. convert block to relational algebra
3. consider alternative query plans for each block
4. select plan with lowest estimated cost

Break query into blocks

- **query block**: any statement starting with select
  - unit of optimisation
  - inner most block optimised first, then move outwards

Relational algebra equivalences

- Selections

Cascade

$$\sigma_{c_1 \wedge \ldots \wedge c_n}(R) = \sigma_{c_1}(\ldots(\sigma_{c_n}(R)))$$

Commute

$$\sigma_{c_1}(\sigma_{c_2}(R)) = \sigma_{c_2}(\sigma_{c_1}(R))$$

- Projections

Cascade

$$\pi_{a_1}(R) = \pi_{a_1}(\ldots(\pi_{a_n}(R)))$$

Where a_i is a set of attributes of R and $a_i \subseteq a_i + 1$ for $i = 1..n-1$

- projection also commutes with selection that only uses attributes retained by the projection

- Joins

Associative

$$R \bowtie (S \bowtie T) = (R \bowtie S) \bowtie T$$

Commutative

$$R \bowtie S = S \bowtie R$$

- consequences:
  - allow you to push down selections and projections before joins
    * care needed for projection
  - allows you to choose different join order, and pick minimum cost option

Statistics and Catalogs

- **system catalog** provides optimiser with information about relations and indexes
- typically contains:
  - number of tuples, number of pages per relation
  - number of distinct keys for each index/attribute
  - low/high values
  - index height
  - number of index pages
- statistics are updated periodically

Cost Estimation

- for each plan, estimate the cost:
  - estimate result size for each operation in tree
  - estimate cost of each operation in tree

$$\text{ResultSize} = \Pi_{j=1\ldots k}\text{NTuples}(R_j)\Pi_{i=1\ldots n}RF_i$$

Reduction Factors

Condition	Reduction Factor
col = value	$\frac{1}{\text{NKeys(col)}}$
col > value	$\frac{\text{High(col)} - \text{value}}{\text{High(col)} - \text{Low(col)}}$
col < value	$\frac{\text{value} - \text{Low(col)}}{\text{High(col)} - \text{Low(col)}}$

Condition	Reduction Factor
Col_A = Col_B (join)	$\frac{1}{\max(\text{NKeys}(Col_A), \text{NKeys}(Col_B))}$
no info	Use magic number 1/10

14. Query Optimisation 2

Single-relation plans

- each available access path (file scan/index) is considered
- choose lowest cost option
- heap scan is always available
- indexes are alternatives if they match selection predicates
- other operations may be performed on top of access but they don't typically incur additional cost as they are done on the fly (e.g. projection, non-matching predicates)

Multi-relation plans

1. select order of relations
2. select join algorithm for each join
3. for each input relation select access method (heap scan, …)

- restrict plan space to **left-deep join trees**

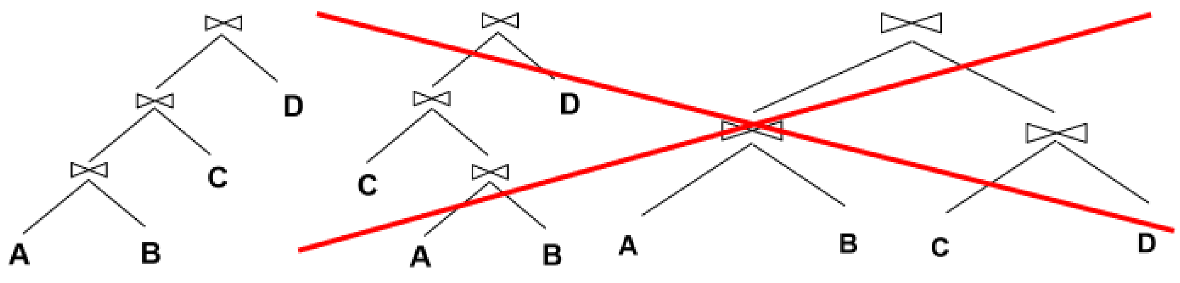


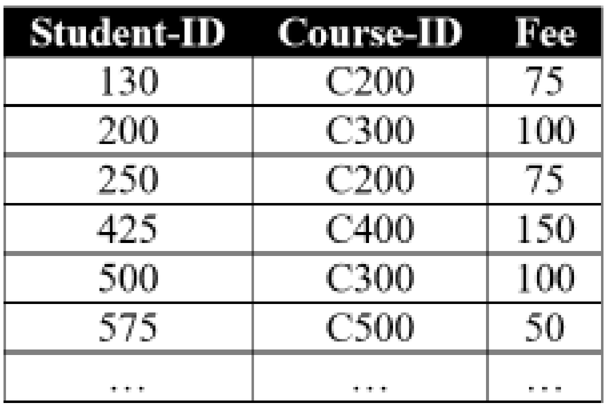
Figure 14: left-deep-join-tree

- allows you to pipeline results from intermediate operations: you don't write back to disk, and then incur cost when you need to read again, you just feed it into the next operation

- prune plans from the tree with cross products immediately

15. Normalisation

Motivation for Normalisation



Student-ID	Course-ID	Fee
130	C200	75
200	C300	100
250	C200	75
425	C400	150
500	C300	100
575	C500	50
...	...	...

Figure 15: denormalised-data

- anomalies in denormalised data
  - **insertion**: cannot add new course until at least one student is enrolled
  - **deletion**: if student 425 withdraws, the course is lost
  - **update**: if the fee changes for a course, every row referencing that course will have to be updated. It would be easy to make inconsistent changes: if the fee changes for a course, every row referencing that course will have to be updated. It would be easy to make inconsistent changes.
- **normalisation**: technique to remove undesired redundancy from databases by breaking a large table into several smaller tables
- **a relation is normalised if all determinants are candidate keys**

Functional dependency

- **functional dependency**: set of attributes X **determines Y if each value of X is associated with only one value of Y
  - $X \rightarrow Y$: X determines Y; if I know X, then I also know Y

Consider **A(X PK, Y PK, Z, D)**: - **determinants**: $X, Y \rightarrow Z$ - X, Y are determinants - **key/non-key attributes**: each attribute is/isn't a part of the primary key - **partial functional dependency**: $Y \rightarrow Z$ - functional dependency of 1+ non-key attributes upon part (not all) of primary key - presence indicates normalisation required - **transitive dependency**: $Z \rightarrow D$ - functional dependency between 2+ non-

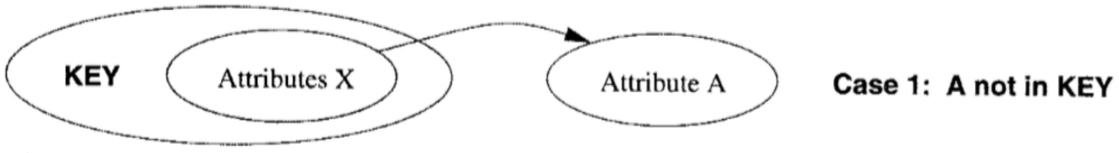


Figure 19.7 Partial Dependencies

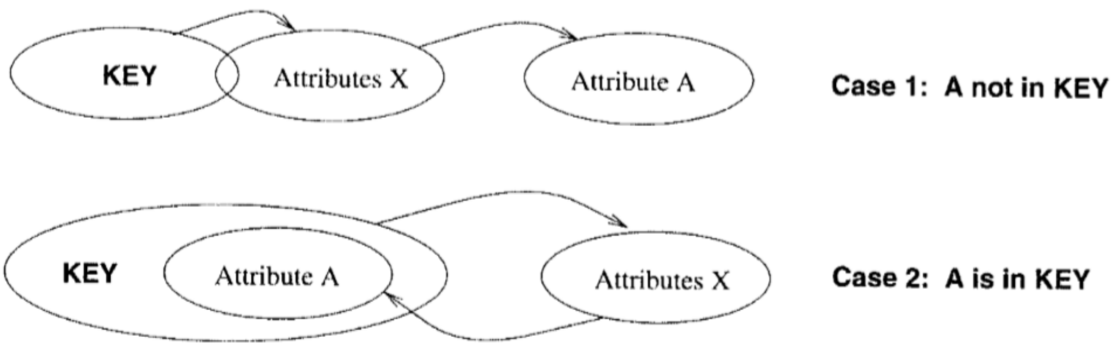


Figure 19.8 Transitive Dependencies

key attributes
Armstrong's Axioms

Steps in Normalisation

Wikipedia: normalisation

- 1st Normal Form: keep atomic data
  - atomic columns: cells have a single value
  - in 1NF if every field contains only atomic values, i.e. no lists or sets
- 2nd Normal Form: remove partial dependencies
  - in 2NF non-key attribute cannot be identified by part of a composite key
- 3rd Normal Form: remove transitive dependencies
  - in 3NF non-key attribute cannot be identified by another non-key attribute

Normalisation vs Denormalisation

- normalisation:
  - minimal redundancy
  - allows users to insert, modify, delete rows without errors/inconsistencies
- denormalisation:
  - improved query speed and performance. Good for time-critical operations
  - extra work on updates to ensure data is consistent

16. Database Administration

- capacity planning: estimating disk space, transaction load
- backup and recovery: failures, responses, backups

Capacity Planning

- **capacity planning**: predicting when future loads will saturate the system
  - determining cost-effective way of delaying saturation as much as possible
- database implementation: need to consider, both at go-live and through-life
  - disk space requirements
  - transaction throughput (transaction/unit time)
  - will be a consideration at system design phase, and system maintenance phase
- many vendors sell capacity planning tools, which all function in a similar manner

Transaction load

- how often will each business transaction run?
  - what SQL statements run for each transaction?

Storage requirements

- treat DB size as sum of all table sizes

    - `table size = number of rows * avg row width`
    - MySQL data type sizes

- estimate table growth rate
    - use system analysis to determine growth rate of tables over time
- project total storage requirements over time
- note this is a rough estimate. Haven't accounted for size of indexes, …

Backup and Recovery

Motivation

- **backup**: copy of data
    - data can become corrupted, deleted, held to ransom
    - backup allows restoration
- **backup and recovery strategy** needed
    - how to back up data
    - how to recover data
- backups protect from:
    - human error: accidental deletion
    - hardware/software malfunction: bugs, hard drive failure, memory failure
    - malicious activity: security compromise
    - disasters: flood, terrorist attack
    - government regulation: historical archiving, privacy

Failure

Some failure categories include:

- **statement failure**: syntactically incorrect
    - no backup required
- **user process failure**: process doing the work fails. Restart the application.
    - no backup required
    - transactions should handle issues with atomic operations

- **network**: connection lost etc.
  - no backup required, re-establish connection
- **user error**: accidental drop table
  - backup required
- **memory failure**: primary memory fails, becomes corrupt
  - backup may be required
- **media failure**: disk failure, corruption, deletion
  - backup required

Backup Taxonomy

Physical vs Logical

- **physical**: raw copies of files and directories, including logs
  - suitable for *large databases* needing *fast recovery*
  - DB preferably offline (cold backup) when backup occurs
  - only portable to machines with similar configuration
  - to restore:
    * shut down DBMS
    * copy backup over current structure on disk
    * restart DBMS
- **logical**: backup completed through SQL queries
  - slower than physical backup: SQL select vs OS copy
  - output larger than physical
  - doesn't include log/config files: this may be important! e.g. for a bank
  - portable: machine independent
  - server available during backup
  - creating backup with mySQL: `mysqldump`, `SELECT ... INTO OUTFILE`
  - restore process: `mysqlimport`, `LOAD DATA INFILE`

Online vs Offline Backup

- **online, hot**: backup occurs when DB is live

    - clients unaware backup in progress
    - needs appropriate locking to ensure data integrity
- **offline, cold**: DB is stopped for backup
    - to prevent disrupting availability, backup could be taken from a replication server while other servers remain live
    - simpler to perform
    - preferable, but not always possible (e.g. when downtime cannot be tolerated)

Full vs Incremental Backup

- **full**: complete DB is backed up, whether physical/logical, online/offline
    - includes everything needed to get DB operational in event of a failure
- **incremental** only changes since last backup are backed up
    - for most DBs this means backup log files
    - to restore:
        * stop DB, copy backup up log files to disk
        * start DB and tell it to redo the log files

Onsite vs Offsite Backup

- **offsite**: store copy of backup offsite
    - enables disaster recovery, as backup is not physically near disaster site
    - e.g. backup tapes stored in vault, backup to cloud, remote mirror databases maintained via replication

Backup Policy

- strategy: usually combination of full and incremental backups
- e.g. weekly full backup, weekday incremental backup
- conduct backups when load is low
- if using replication: use mirror DB for backups to negate performance concerns with primary DB
- test backup and restore process before it is needed

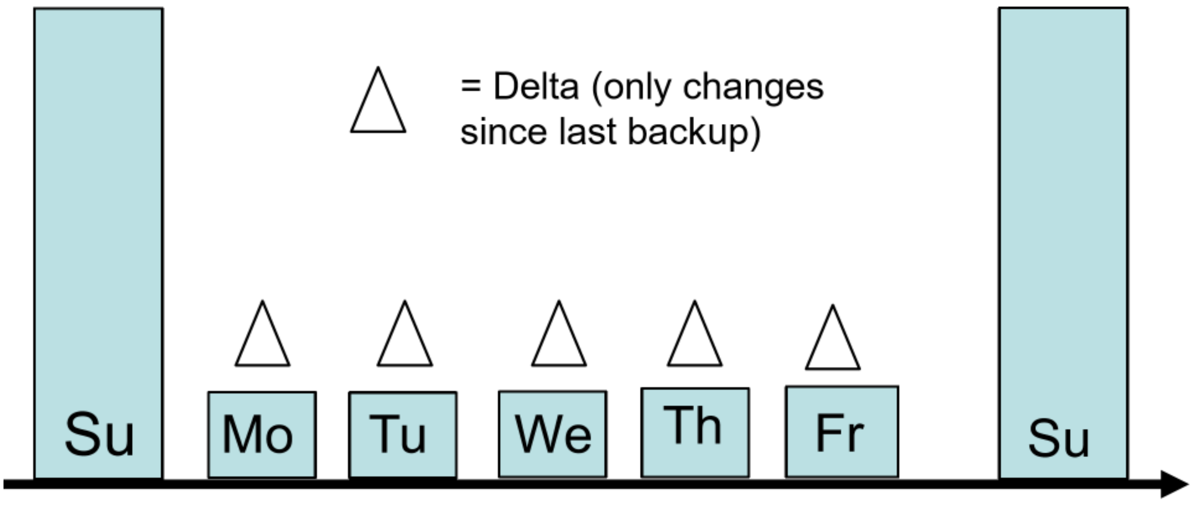


Figure 16: backup-policy

17. Transactions

Transactions

transaction: logical unit of work - **indivisible/atomic**: must be either fully completed or else aborted - DML statements are atomic - successful transaction changes database from one consistent state to another, i.e. all data integrity constraints are satisfied - DBMS provides **user-defined transactions**: sequence of DML statements - solve 2 problems: - need to define unit of work - concurrent access

Defining a unit of work

- users need method to define unit of work
- transaction: multiple SQL statements embedded within larger application
  - needs to be indivisible
- in case of error:
  - SQL statements already completed need to be reversed
  - pass error to user
  - when ready, user can retry transaction
- e.g. withdrawal from a bank:

    - `SELECT`: get starting account balance
    - `INSERT`: insert detailed representation of the withdrawal
    - `UPDATE`: update account balance

- MySQL implementation: `BEGIN, COMMIT, ROLLBACK`

```
START TRANSACTION;   # also BEGIN
  # <SQL statements>
COMMIT;          # commit whole transaction
ROLLBACK;        # undoes everything
```

ACID: Transaction properties

- **atomicity**: transaction is a single, indivisible, logical unit of work
    - all operations within the transaction must be completed, otherwise the transaction must be wholly aborted
- **consistency**: constraints holding before transaction also need to hold after it
    - multiple users accessing same data see same value
- **isolation**: changes during execution cannot be seen by other transaction until completed
    - as the change could be rolled back, this prevents others acting on invalid data
- **durability**: once complete, changes made by a transaction are permanent and recoverable if system fails

Concurrent Access

- multiple users accessing database at same time, can produce
- **lost updates**: Alice and Bob read account balance near simultaneously, then withdraw money. Alice and Bob are both unaware of the other person's withdrawal. Whoever submits the update to account balance first will have the value overwritten by the other persons update, and the account balance won't have the expected value

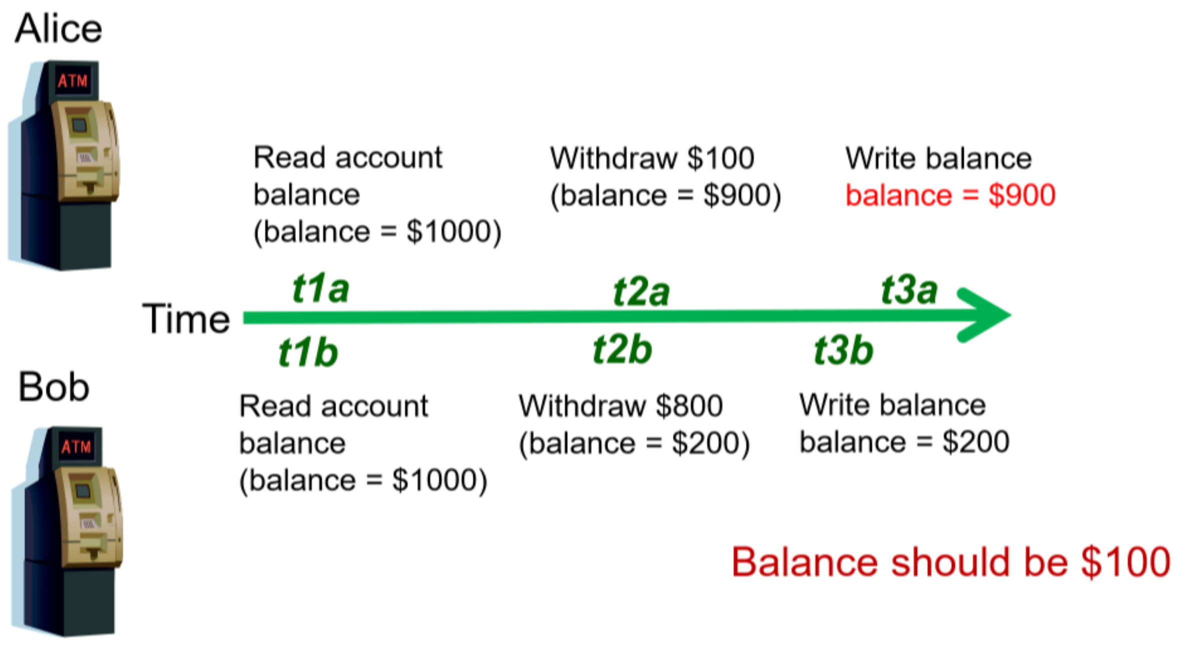

Alice
Read account balance (balance = $1000)
Withdraw $100 (balance = $900)
Write balance balance = $900
Time
t1a
t2a
t3a
t1b
t2b
t3b
Bob
Read account balance (balance = $1000)
Withdraw $800 (balance = $200)
Write balance balance = $200
Balance should be $100

Figure 17: lost-update-problem

- **uncommitted data**: two transactions execute concurrently. The first is rolled back after the second has already accessed it.

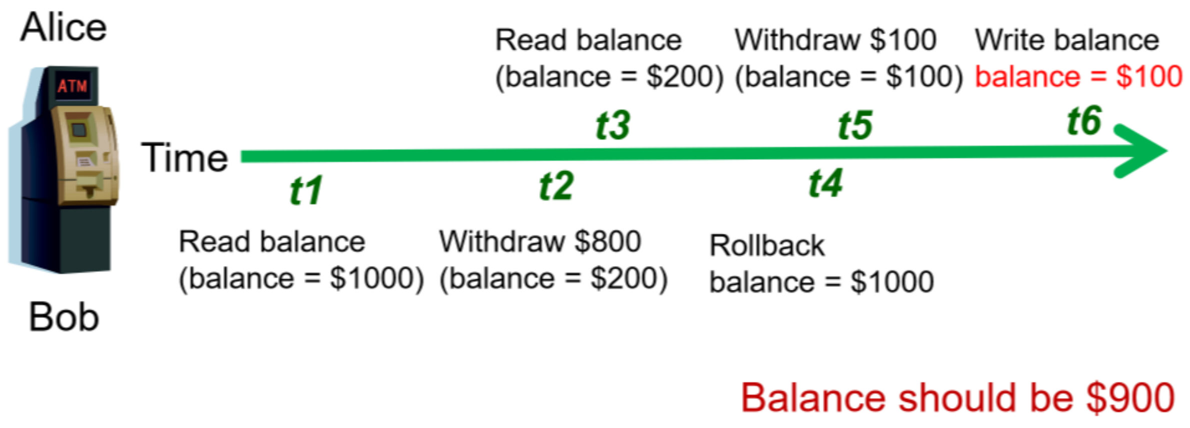
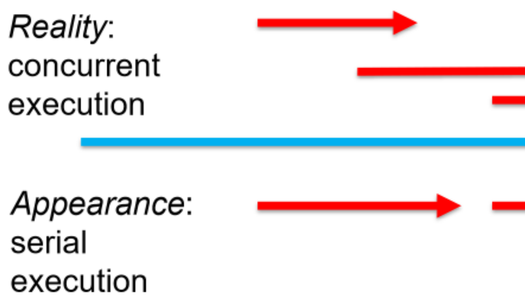

Alice
Read balance (balance = $200)
Withdraw $100 (balance = $100)
Write balance balance = $100
Time
t3
t5
t6
t1
t2
t4
Read balance (balance = $1000)
Withdraw $800 (balance = $200)
Rollback balance = $1000
Bob
Balance should be $900

Figure 18: uncommitted-data-problem

- **inconsistent retrieval**: one transaction calculates aggregate over set of data, during which time other transactions update the data. Some data may be read before the change, others after the change, producing inconsistent results

Serialisability

- ideally transactions can be serialised, such that multiple concurrent transactions appear as if they execute one after the other
  - this ensures consistency


Reality: concurrent execution
Appearance: serial execution

  - very expensive: lots of time because blocking unnecessarily

Concurrency Control Methods

- DBMS creates schedule of read/write operations for concurrent transactions
- interleave execution of operations with concurrency control algorithms
- methods:
  - locking: primary method
  - timestamping
  - optimistic

Locking

- **lock**: guarantee exclusive use of data item to current transaction
  - prevents another transaction from reading inconsistent data
  - T1 acquires lock prior to data access
  - lock released once transaction complete
  - T2 cannot access data until lock us available
- **lock manager**: responsible for assigning, policing locks

Lock Granularity

- **database-level**: entire database locked

  - good for batch processing
  - unsuitable for multi-user DBMS
  - T1, T2 cannot access same DB concurrently, even if they are accessing different tables
  - SQLite, Access

- **table-level**: entire table locked
  - similar to above, but not as bad
  - T1, T2 can access same DB concurrently as long as they are working on different tables
  - bottlenecks still exist if transactions want to access different parts of the table and wouldn't interfere with one another
  - not suitable for highly multi-user DBMS
- **page-level**: lock set of tuples on a disk page
  - not commonly used
- **row-level**: allow concurrent transaction to access different rows of same table, even if located on same page
  - good availability
  - high overhead: each row has a lock that must be read and written to
  - most popular approach: MySQL , Oracle
- **field-level**: concurrent access to same row as long as accessing different attributes
  - most flexible
  - extremely high overhead
  - not commonly used

Lock types

- **binary lock**: locked (1), unlocked(0)
  - handles lost update problem: lock not released until statement completed
  - too restrictive to yield optimal concurrency: locks even for 2 `READ`s
- **exclusive and shared lock**
  - **exclusive**: access reserved for transaction that locked it
    * must be used for transaction intending to `WRITE`
    * granted iff no other locks (exclusive or shared) held on the data item
    * MySQL: `SELECT ... FOR UPDATE`

  - **shared**: grant `READ` access
    * transaction wants to `READ` data, and no exclusive lock is held on the item
    * multiple transactions can have shared lock on same data if they are all just reading it
    * MySQL: `SELECT ... FOR SHARE`

Deadlock

- **deadlock**: when 2 transactions wait for each other to unlock data
  - T1 locks X, wants Y
  - T2 locks Y, wants X
  - could wait forever if not dealt with
  - only happens with exclusive locks
- handle by:
  - prevention
  - detection

Timestamping

- **timestamp**: assign globally unique timestamp to each transaction
  - each data item accessed by the transaction gets the timestamp
  - thus for every data item, the DBMS knows which transaction performed last read/write
  - when transaction wants to read/write, DBMS compares timestamp with timestamp already attacked to item and decides whether to allow access

Optimistic

- based on assumption that majority of DB operations do not conflict
- transaction executed without restrictions/checking
- when ready to commit: DBMS checks whether it/any of data it read has been altered
  - if so, rollback

Transaction Log

- allows restoration of database to previous consistent state

- DBMS tracks all updates to data in **transaction log**:
  - record for beginning of transaction
  - for each SQL statement:
    * operation (update, delete, insert)
    * objects affected
    * before/after values
    * pointers to previous/next transaction log entries
    * commit/ending of transaction
- also allows restoration of corrupted database

18. Data Warehousing

Data Warehousing

Motivation

- relational databases used to run day-to-day business operations
  - automation of routine business processes: accounting, inventory, sales, …
- problems:
  - too many of them: each department has multiple, often of different types
  - produces many of the problems databases are meant to solve:
    * duplicated, inaccessible, inconsistent data
- managers want data for analysis and decision making
- need means to get integrate all organisational data: **informational database**, rather than **transactional database**
  - allows all of organisation's data to be stored in manner that supports organisational decision processes
  - end user is not writing to it, just reading from it
- **data warehouse**: single repository of organisational data
  - integrates data from multiple sources
  - extracts data from source systems, transforms, loads into warehouse
  - makes data available to managers to support analysis and decision making
  - large data store ~ TB-PB

Analytical Queries

- **operational questions**: e.g. Customer service: help I forgot my membership card
  - typically references small number of tables
- **analytical questions**: e.g. campaign management: how many customers purchased $x of products in Melbourne stores?
  - typically references large number of tables
- data warehousing supports analytical queries
  - numerical aggregations: how many? average? total cost?
  - attempting to understand relative to dimensions: sales by state by customer type

DW Characteristics

- **subject oriented**: organised around subjects (customers, products, sales)
- **validated, integrated data**:
  - data from different systems converted to common format allowing comparison and consolidation
  - data is validated
- **time variant**: stores historical data
  - trend analysis
  - data is a series of time-stamped snapshots
- **non-volatile**
  - users have read only access
  - updating done automatically by Extract/Transform/Load process, periodically by DBA

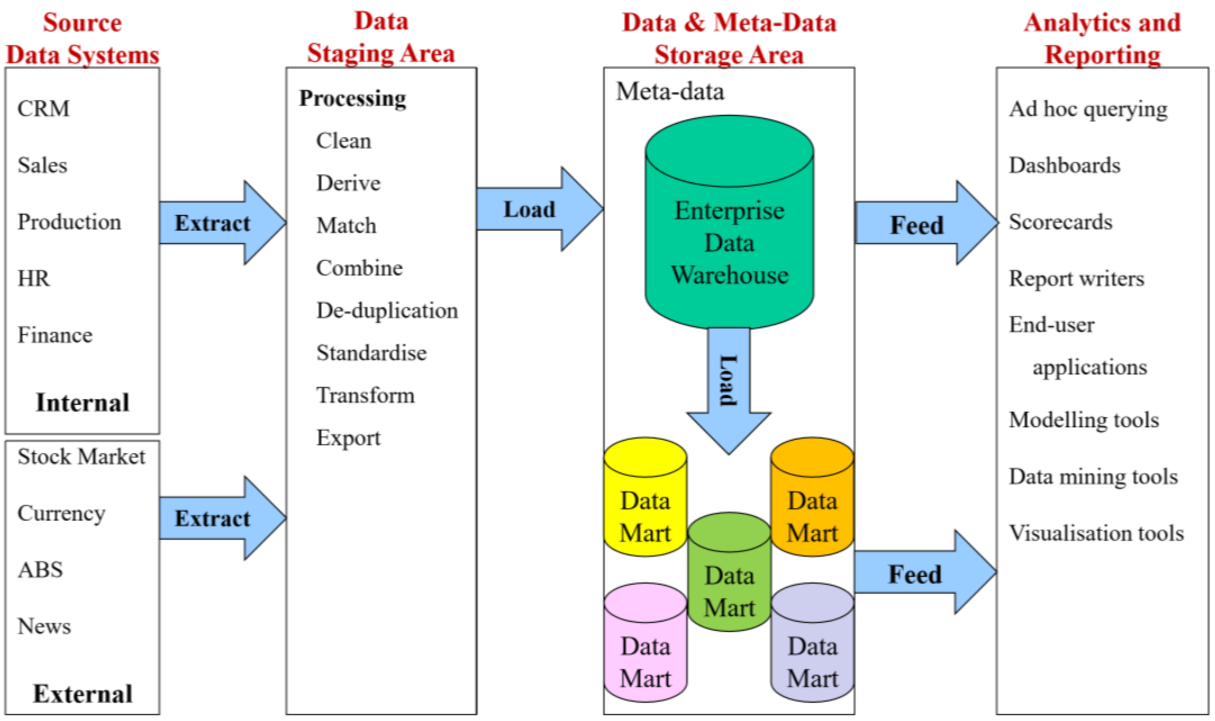


Figure 19: data-warehouse-architecture

- allow you to:
  - build Business Intelligence dashboard
  - perform advanced analysis

Dimensional Modelling

e.g. How much *revenue* did *product G* generate in the *last 3 months*, broken down by month for south easter sales *region*, by individual _stores, broken down by *promotions*, compared to estimates and to the previous product version

- dimensional analysis: supports business analyst view
- Revenue per product per customer per location
- fact: revenue
- dimensions: product, customer, location

Dimensional model

- **dimensional model**: simple, restricted ER model
- **fact table**: contains business measures/facts, with FKs pointing to dimensions
  - these are the values the manager is interested in
  - granularity: level of detail; e.g. time period months/days

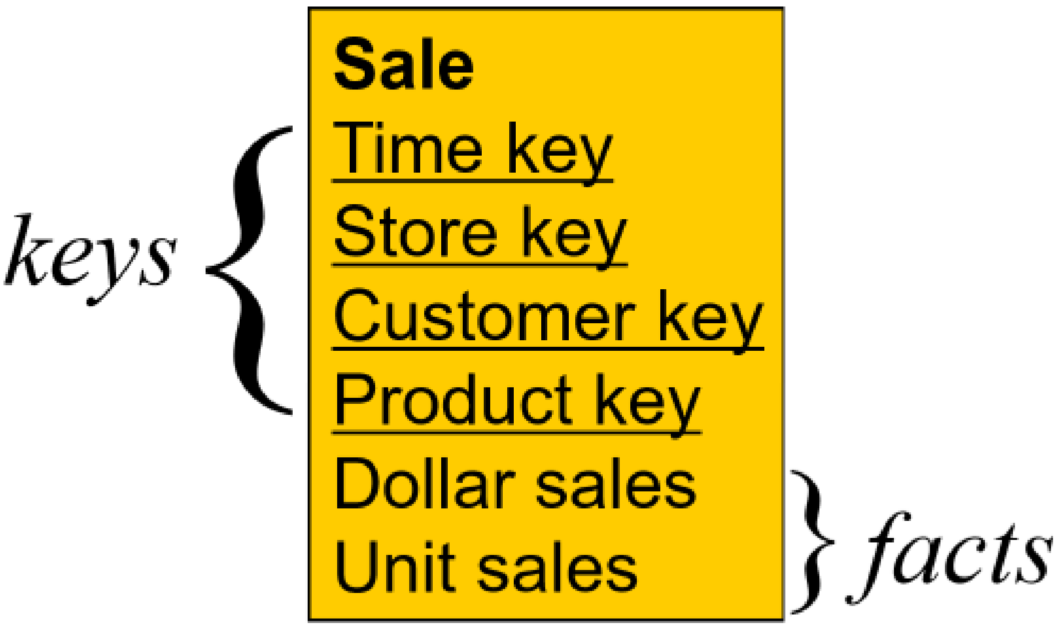


Figure 20: fact-table

- **dimensional tables**: captures factor by which fact can be described/classified
  - sometimes hierarchies in dimensions
- **star schema**

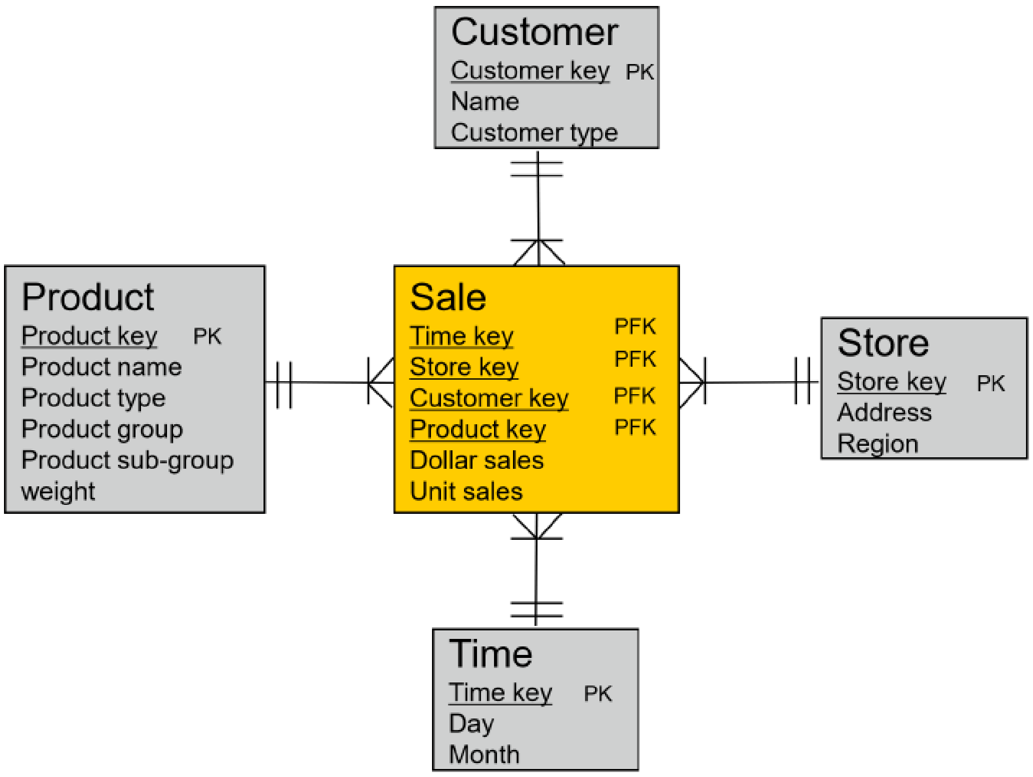


Figure 21: star-schema

Designing a dimensional model

1. choose a business process (subject)
2. choose measured facts (usually numeric, additive quantities)
3. choose granularity of fact table
4. choose dimensions
5. complete dimension tables

Embedded Hierarchies

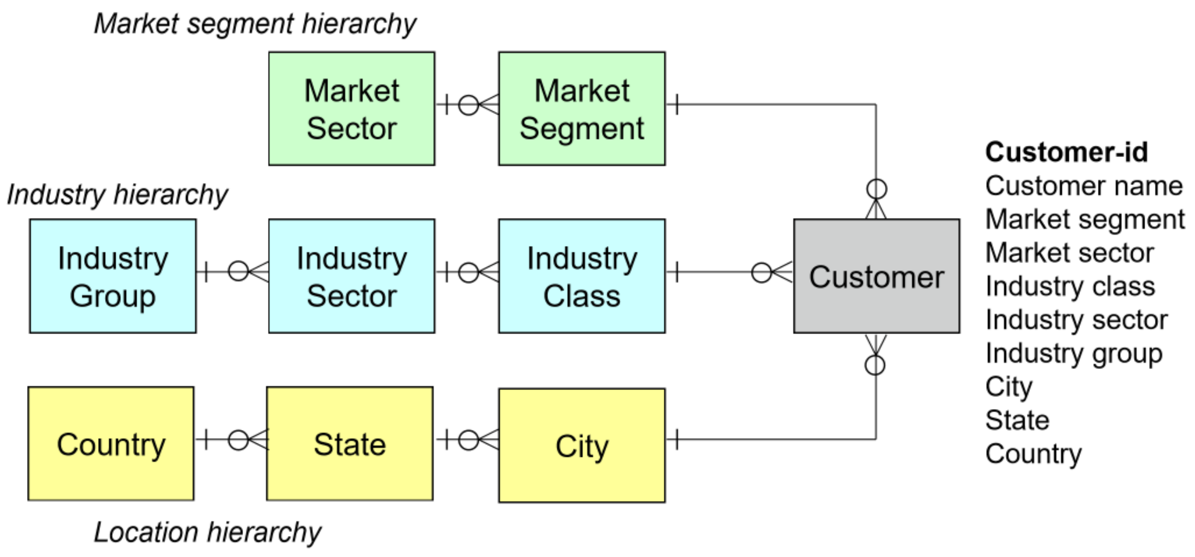


Figure 22: embedded-hierarchy

Snowflake schema

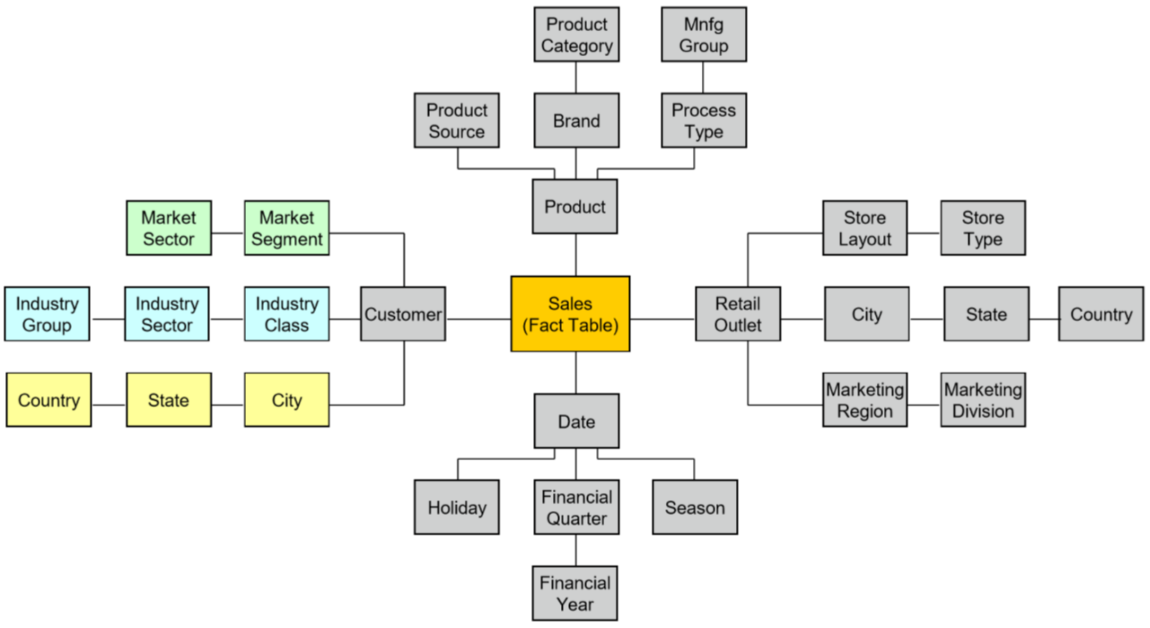


Figure 23: snowflake-schema

Denormalisation

- DW is typically denormalised
- denormalised produces:
  - fewer tables
  - fewer joins
  - faster queries
  - design tuned for end-user analysis
- data is read only and consistent from ETL process, so no risk of anomalies from unnormalised DB

19. Distributed Databases

Distributed Databases

- **distributed database**: single logical database physically spread across multiple computers in multiple locations, all connected via data communications link
  - appears to user to be a single database
  - focus here
- **decentralised database**: collection of independent databases which are not networked together as one logical database
  - users see many databases

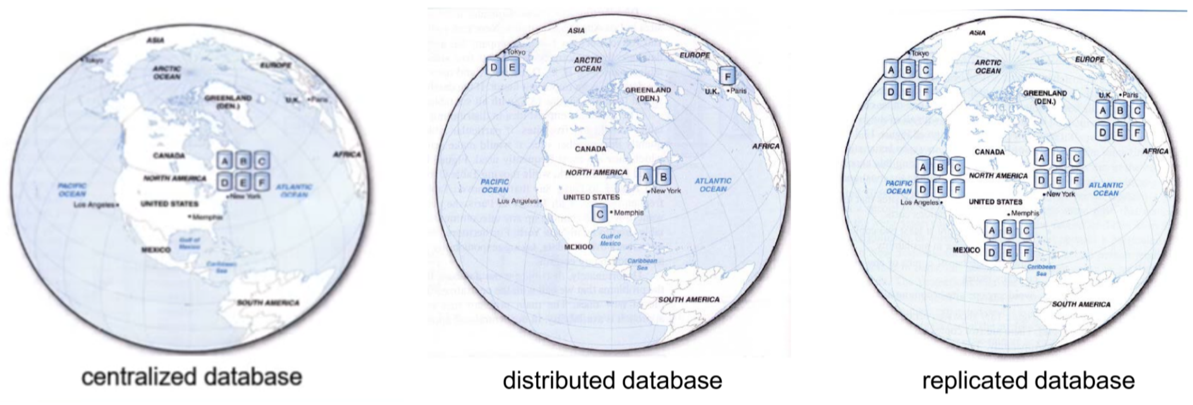


Figure 24: distributed-database

- physical servers have their own internal memory structures

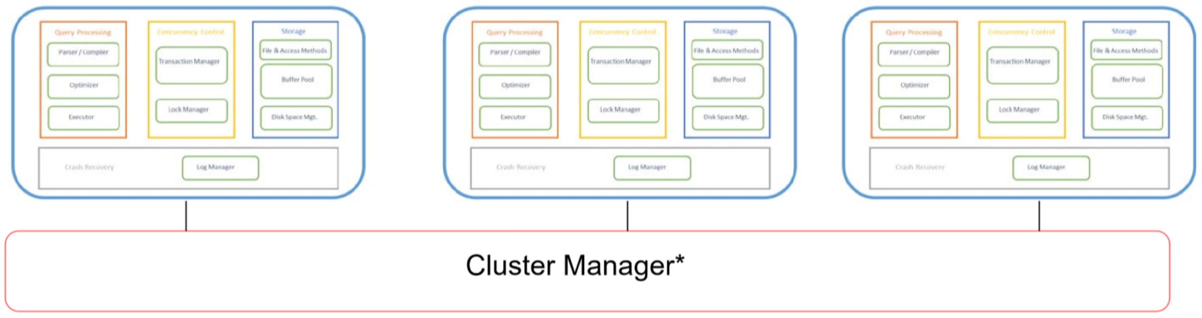


Figure 25: cluster-manager

- **cluster manager**: coordinates communication between physical servers

Advantages

- good fit for geographically distributed organisations/users
- data can be located near sites with greatest demand: e.g. store sport info near the point of interest: AFL - Melbourne, NFL - New York, etc.
- faster data access (for local data)
- faster data processing: workload shared between physical servers

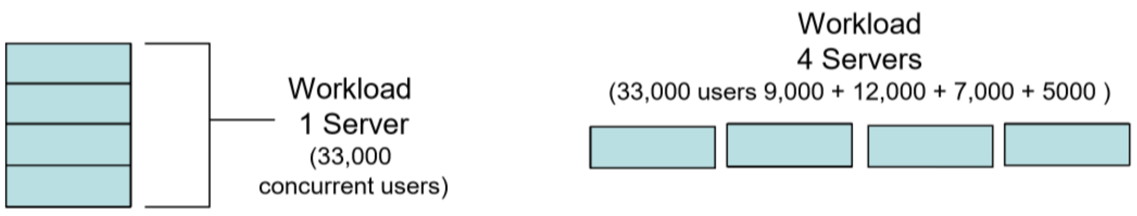


Figure 26: workload-distributed

- modular growth: add new servers as load increases
- increased reliability/availability: less likely to have single point of failure
- supports database recovery: data is replicated across sites

Disadvantages

- **complexity** of management and control

  - who/where is current version of record?
  - who is waiting to update information?
  - how does this get displayed to user?

- **data integrity**: additional exposure to improper updating
  - simultaneous updates from different locations: which should be chosen?
  - solutions:
    * transaction manager
    * master-slave design: master allowed to write, slaves read only
- **security**: many server sites means higher risk of breach
  - protection needed from cyber and physical attacks
- **lack of standards**: different RDDBMS vendors use different protocols
- **training/maintenance costs**: more complex IT infrastructure
  - increased disk storage ($)
  - fast intra/inter network infrastructure ($$$)
  - clustering software ($$$$)
  - network speed ($$$$$)
- **increased storage requirements**: replication

Objectives and Trade-offs

- **location transparency**: user doesn't need to know where data are stored
  - requests to retrieve/update data from any site are forwarded by the system to theX relevant site for processing
  - all data in the network appears as a single logical database stored at a single site as far as the user can tell
  - a single query could join data from tables in multiple sites
- **local autonomy**: node can continue to function for local users if connectivity lost
  - users can administer local database: local data, security, log transactions, recovery
- **trade-offs**:
  - availability vs consistency: DB may be unavailable while updating, but more consistent
  - synchronous vs asynchronous update
    * e.g. banking: synchronous; social networks: asynchronous

Distribution Options

- some combination of below options is also typical

Data Replication

- **data replication**: data copied across sites
- advantages
  - currently popular approach for high availability global systems: implemented by most SQL and NoSQL DBs
  - high reliability: redundant copies of data
  - fast access at location where most accessed
  - can avoid complicated distributed integrity routines, with replicated data being refreshed at specified intervals
  - if a node goes down availability is largely unaffected
  - reduced network traffic at prime time if updates can be delayed
  - need more storage space: each server stores a copy of each tuple
- disadvantages
  - may need to be tolerant of out-of-date data
  - updates could cause performance problems for busy nodes
  - takes time for update operations
  - updates place heavy demand on networks, and high speed networks are expensive

Synchronous Update

- e.g. for banking
- data continuously kept up to date: users anywhere can access data and get the same answer
- if any copy of a data item is updated, the same update is applied immediately to all other copies, otherwise it is aborted
- ensures data integrity
- minimises complexity of knowing where more recent copy of data is
- slow response time, high network usage: time taken to check update accurately and completely propagated

Asynchronous Update

- e.g. for social network

- delay in propagating data updates to remote databases
- application able to tolerate some degree of temporary inconsistency
- acceptable response time: updates happen locally; replicas are synchronised in batches and predetermined intervals
- more complex to plan/design: need to get right level of data integrity/consistency
- suits some systems more than others

Horizontal Paritioning

- **horizontal partitioning**: table rows distributed across sites
- advantages:
  - data stored close to where its used
  - local access optimisation: better performance
  - only relevant data stored locally: good for security
  - combining data: unions across partitions c.f. joins for vertical partitioning: unions are less expensive
- disadvantages
  - accessing data across partitions: inconsistent access speed
  - no data replication: backup vulnerability
    * in practice: typically have partial replication across sites

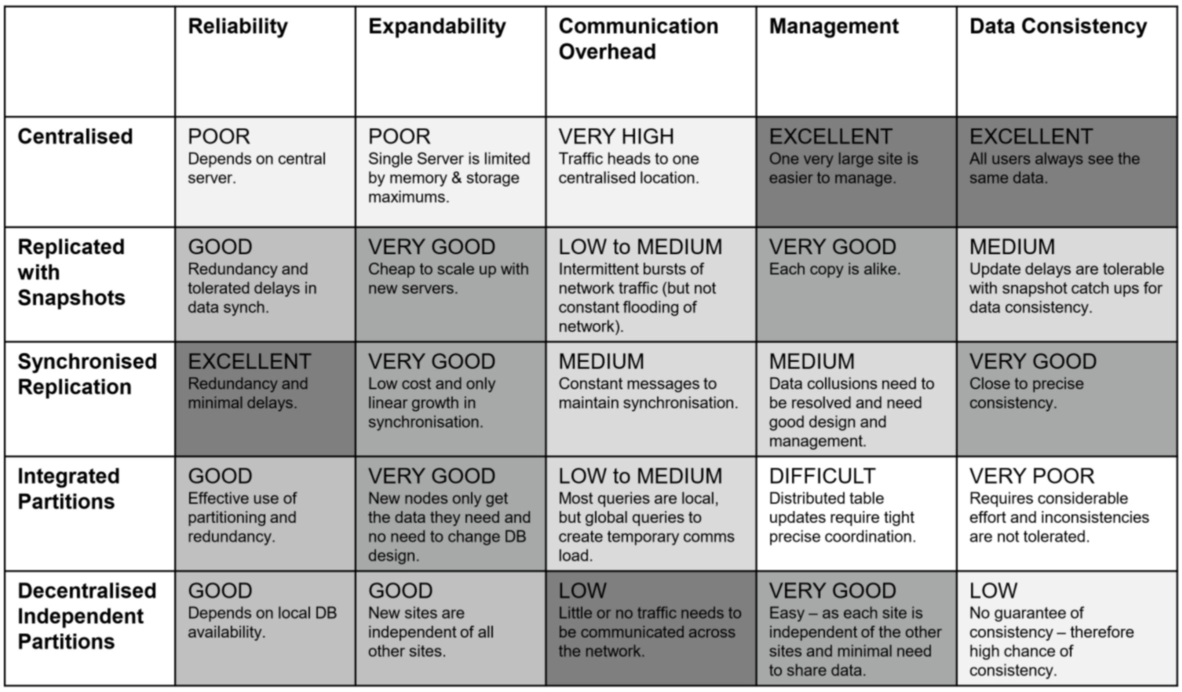
Vertical partitioning

- **vertical partitioning**: table columns distributed across sites
- advantages/disadvantages mostly the same as for horizontal partitioning
- disadvantage:
  - combining data: joins across partitions, more expensive c.f. horizontal partitions

Comparing configurations

- Centralised DB, distributed access:
  - DB at one location accessed from everywhere
- Replication with periodic asynchronous snapshot update
  - DB at many locations, with each copy updated periodically

- replication with near real-time synchronisation of updates
  - DB at many locations, each copy updated in nreal real-time
- partitioned, integrated, one logical database
  - DB partitioned across many sites within a logical DB and single DBMS
- partitioned, independent, non-integrated segments (decentralised)
  - data partitioned across many sites
  - independent, non-integrated segmented
  - multiple DBMS



	Reliability	Expandability	Communication Overhead	Management	Data Consistency
Centralised	POOR Depends on central server.	POOR Single Server is limited by memory & storage maximums.	VERY HIGH Traffic heads to one centralised location.	EXCELLENT One very large site is easier to manage.	EXCELLENT All users always see the same data.
Replicated with Snapshots	GOOD Redundancy and tolerated delays in data synch.	VERY GOOD Cheap to scale up with new servers.	LOW to MEDIUM Intermittent bursts of network traffic (but not constant flooding of network).	VERY GOOD Each copy is alike.	MEDIUM Update delays are tolerable with snapshot catch ups for data consistency.
Synchronised Replication	EXCELLENT Redundancy and minimal delays.	VERY GOOD Low cost and only linear growth in synchronisation.	MEDIUM Constant messages to maintain synchronisation.	MEDIUM Data collusions need to be resolved and need good design and management.	VERY GOOD Close to precise consistency.
Integrated Partitions	GOOD Effective use of partitioning and redundancy.	VERY GOOD New nodes only get the data they need and no need to change DB design.	LOW to MEDIUM Most queries are local, but global queries to create temporary comms load.	DIFFICULT Distributed table updates require tight precise coordination.	VERY POOR Requires considerable effort and inconsistencies are not tolerated.
Decentralised Independent Partitions	GOOD Depends on local DB availability.	GOOD New sites are independent of all other sites.	LOW Little or no traffic needs to be communicated across the network.	VERY GOOD Easy – as each site is independent of the other sites and minimal need to share data.	LOW No guarantee of consistency – therefore high chance of consistency.

Figure 27: comparing-distributed-db-configurations

Functions of a distributed DBMS

- locate data with distributed catalog (statistics + metadata)
- determine location from which to retrieve data and process query components
- translate between nodes with different local DBMS
- data consistency
- global primary key control

- provide scalability, security, concurrency, query optimisation, failure recovery

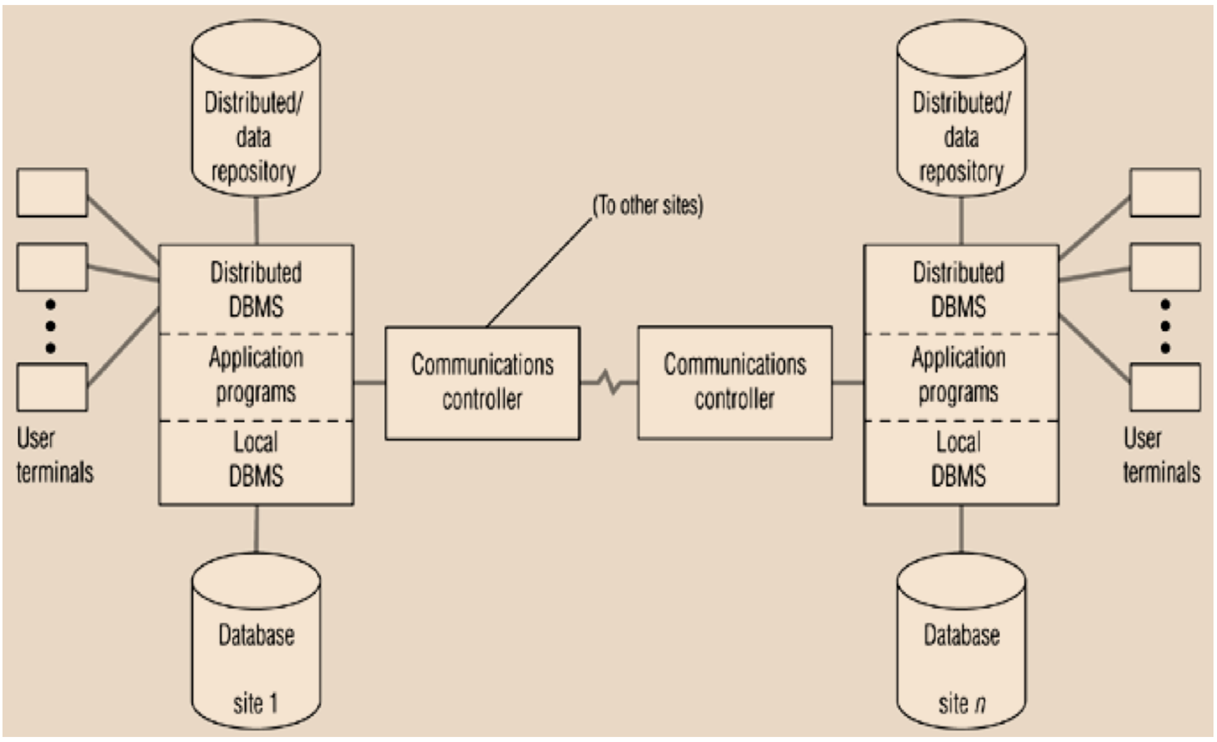


Figure 28: distributed-dbms-architecture

Date's 12 Commandments for Distributed Databases

- represent a target for DDBMS, while most don't satisfy all principles

Independence

1. **Local site independence**: each local site can act as an independent, autonomous, DBMS. Each site is responsible for security, concurrency, control, backup, recovery.
2. **Central site independence**: no site in the network relies on a central site, or on any other site. Each site has the same capabilities.
3. **Failure independence**: system is not affected by node failures. The system is in continuous operation, even in the case of a node failure, or expansion of the network.
4. **Hardware independence**
5. **Operating System independence**
6. **Network independence**
7. **Database independence**

Transparency

8. **Location transparency**: user doesn't need to know location of data to retrieve it
9. **Fragmentation transparency**: data fragmentation is transparent to the user, who sees only one logical database.
10. **Replication transparency**: user sees only one logical database. DDBMS transparently selects database fragments to access.
11. **Distributed query processing**: query may be executed at several different sites. Query optimisation is performed transparently by DDBMS.
12. **Distributed transaction processing**: transaction may update data at several sites, and transaction is executed transparently.

20. NoSQL

Motivation for NoSQL

- relational databases, have a number of **pros**, which explain their dominance:
  - simple, can capture most business use case
  - integrate multiple applications with shared data store
  - SQL, standard interface language
  - ad hoc queries
  - fast, reliable, concurrent, consistent
- relational databases, also have their **cons**:
  - **object-relational impedance mismatch**
  - poor with big data
  - poor with clustered/replicated servers (when you get > 10^6 nodes)
- NoSQL has arisen due to these cons, but relational still relevant
  - often only need eventual consistency

NoSQL Goals

- reduce impedance mismatch: improve developer productivity
- big data: handle larger data volumes and throughput

Object-relational impedance mismatch

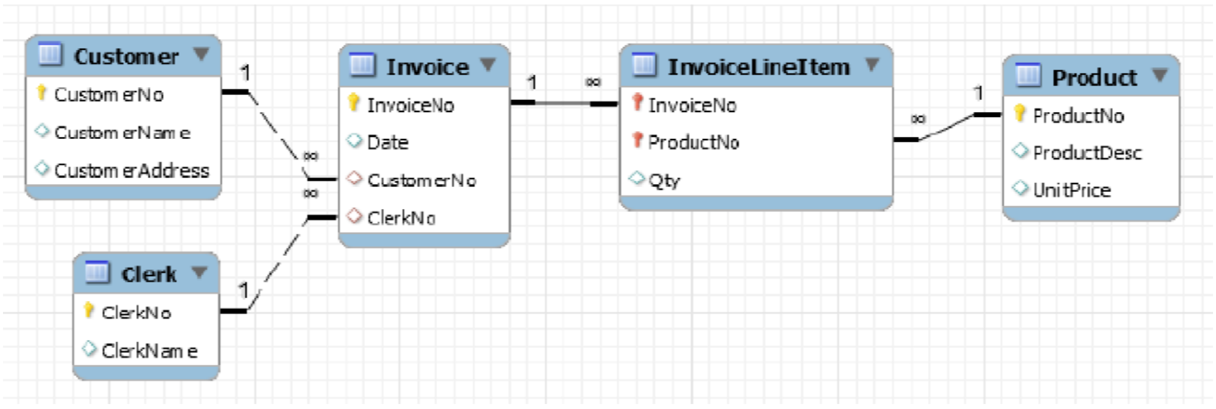


Figure 29: normalised-invoice-eg

- example: invoice with a header of customer details, and a list of objects
  - relational model: data stored in separate tables for order + customer + …
    * cannot model real-world object directly
    * lots of work to disassemble and reassemble aggregate
  - object oriented model: class with composition and inheritance. All data in one place

Wiki

- Difficulty of integrating OOP with relational databases
- Objects reference one another, forming a graph (e.g. with cycles)
- Relational schema is tabular, defining linked heterogeneous tuples

Various types of mismatch, e.g.

- encapsulation: object-relational mappers necessarily expose underlying content, violating encapsulation
- accessibility: in OOP public/private is absolute characteristic of data's state, while in relational model it is relative to need
- classes, inheritance, polymorphism: not supported by relational DB
- type system mismatch: relational model prohibits pointers. Scalar types may be vastly different.
- structural mismatch: objects composed of objects, objects specialise from a more general definition. Difficult to map onto relational schema.
- integrity mismatch: OOP doesn't declare constraints, exception raising protection logic. Relational database requires declarative constraints.

- transactional differences: unit of work in relational DB is much larger than that in OOP
- manipulative differences: SQL vs custom OOP querying

3Vs of Big Data

- **volume**: much larger quantity than typical for relational DB
- **variety**: many different data types, formats
- **velocity**: data comes at high rate

Big Data Characterisitics

- **schema on read**: data model determined later, as dictated by use case (XML, JSON)
  - c.f. **schema on write**: pre-existing data model, approach of relational DB
  - capture and store data, worry about how you want to use it later
- **data lake**: large integrated repository for data without a predefined schema
  - capture everything
  - dive in anywhere
  - flexible access

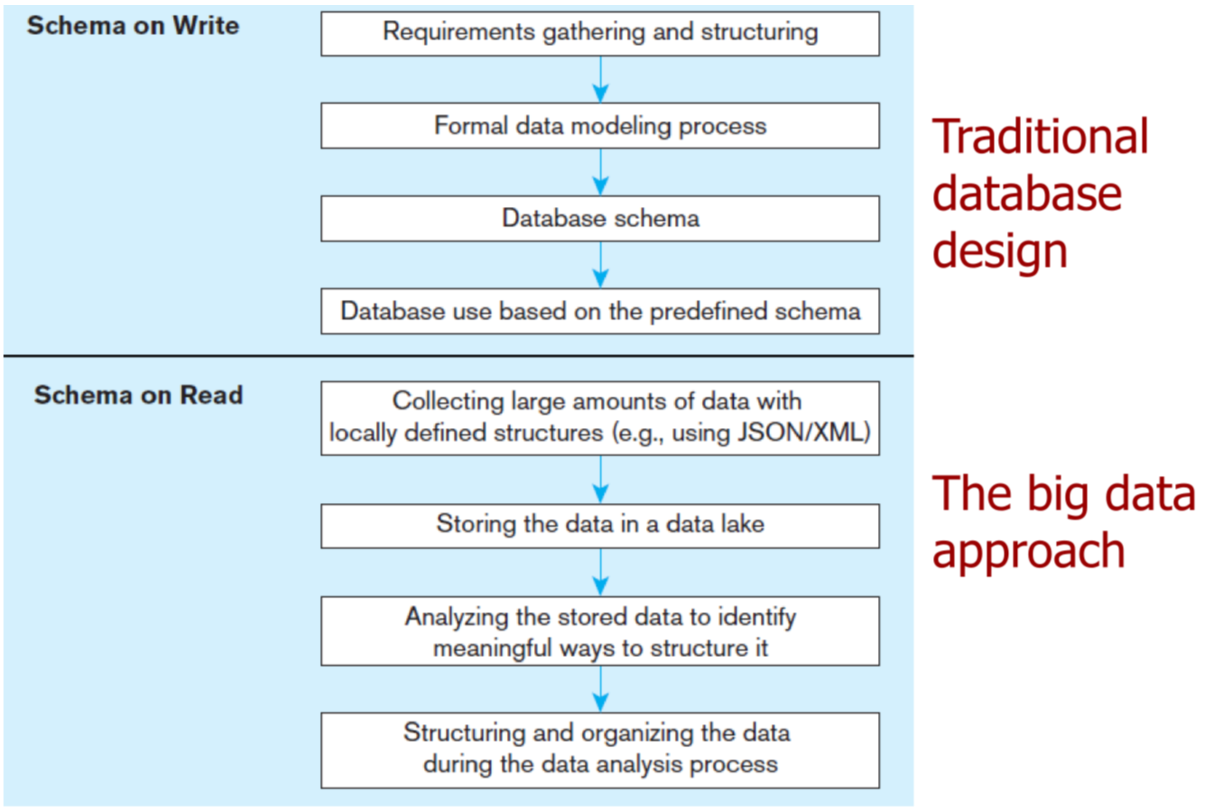

Schema on Write
Requirements gathering and structuring
Formal data modeling process
Database schema
Database use based on the predefined schema
Traditional database design
Schema on Read
Collecting large amounts of data with locally defined structures (e.g., using JSON/XML)
Storing the data in a data lake
Analyzing the stored data to identify meaningful ways to structure it
Structuring and organizing the data during the data analysis process
The big data approach

Figure 30: schema-on-read

NoSQL Features

- doesn't use relational model or SQL
- runs well on distributed servers
- often open source
- build for modern web
- schema-less (often has an implicit schema)
- supports schema on read
- not ACID compliant
- eventually consistent

NoSQL Variants - Aggregate oriented

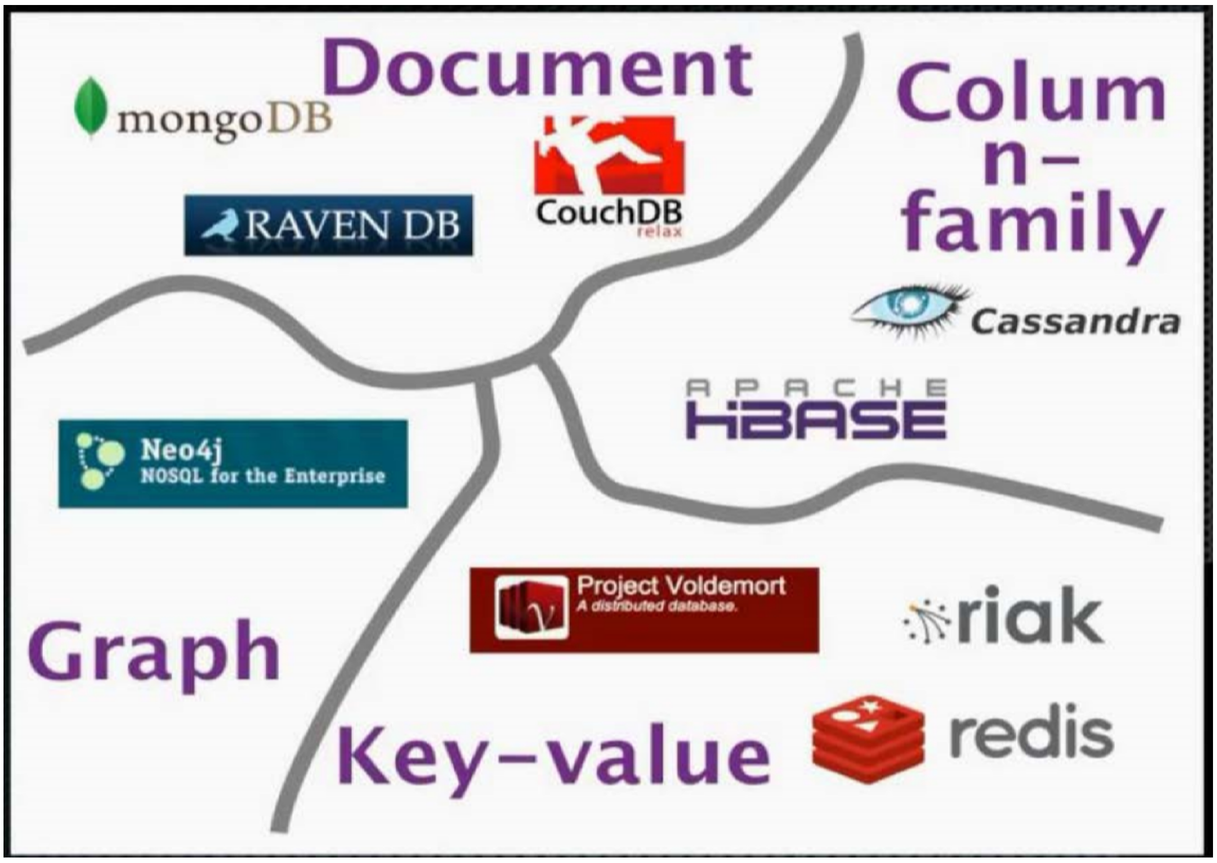


Figure 31: nosql-variants

- **aggregate-oriented** databases store business objects in entirety
- pros
  - entire data stored together. Eliminates need for transactions
  - efficient storage on clusters/distributed DBs
- cons
  - harder to analyse across subfields of aggregates
  - e.g. sum over products instead of over orders

Key-value stores

- simple pair of key and associated collection of values
- database has no knowledge of structure/meaning of values

- key: primary key, usually a string
- value: anything (number, array, image, JSON)
  - up to application to interpret
- operations: put, get, update
- example: Redis, DynamoDB

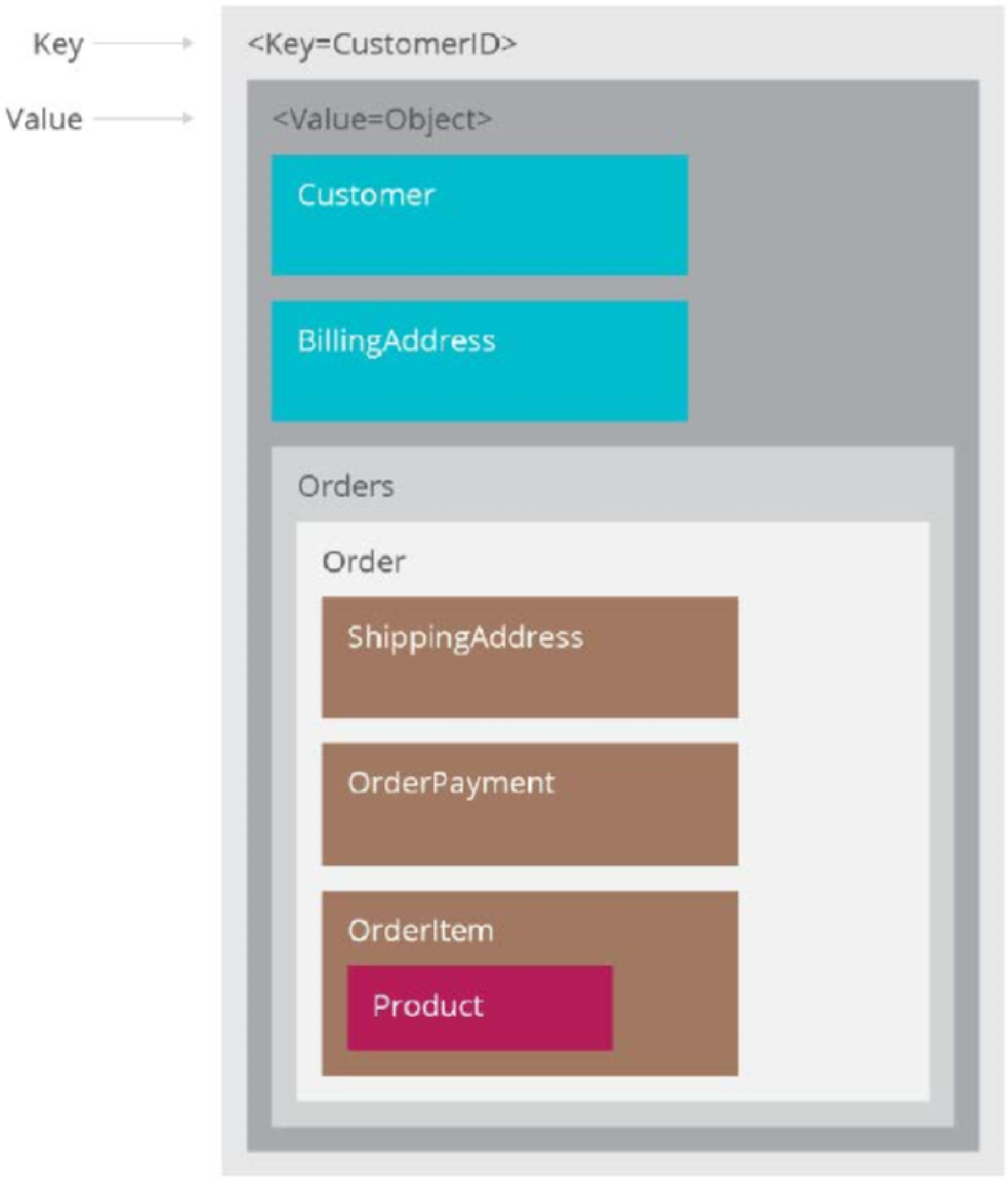
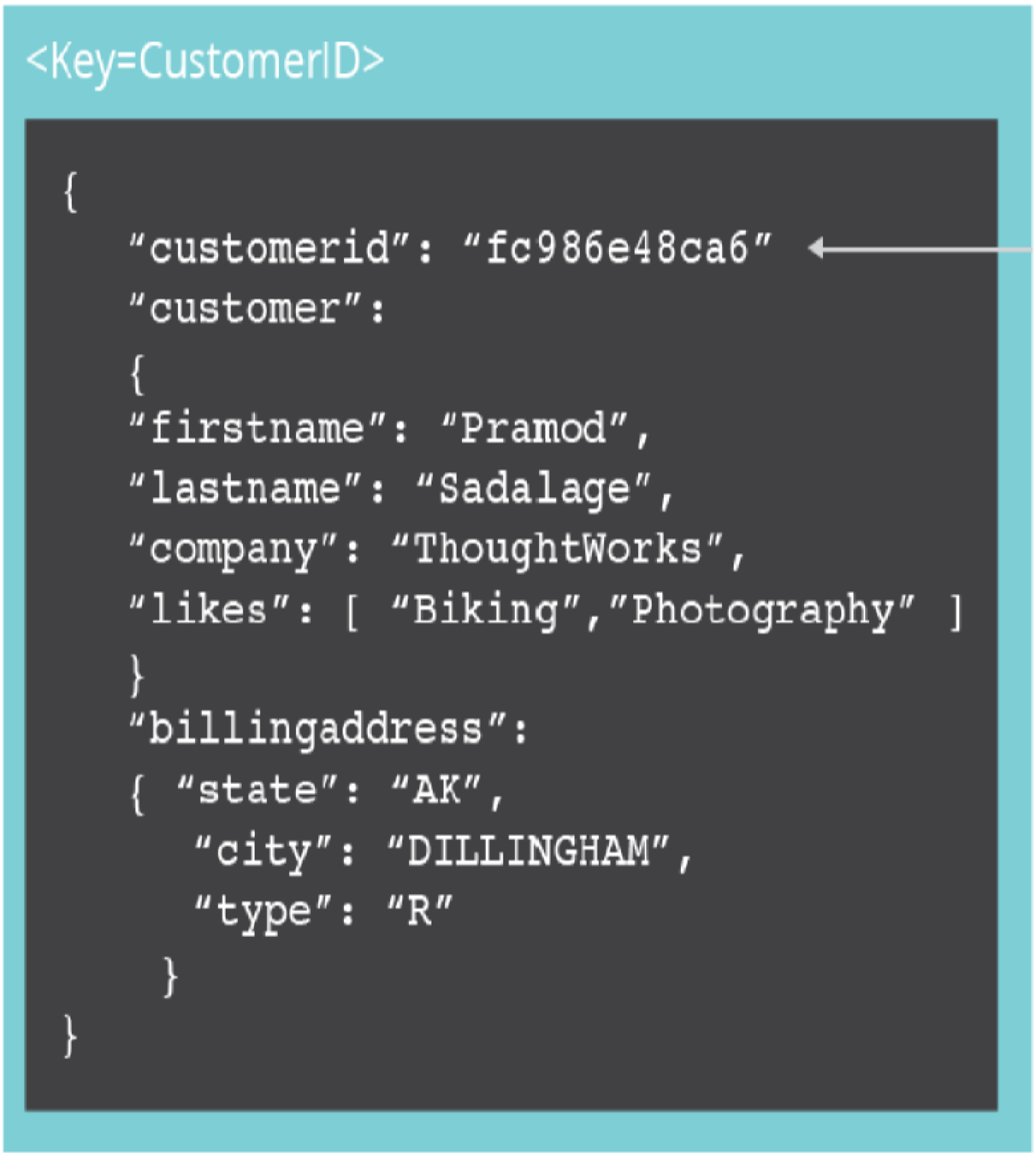


Figure 32: key-value-store

Document database

- similar to KV store, but document is structured, allow manipulation of specific elements separately
- document examinable by database:
  - content can be queried
  - parts of document can be updated
- document: JSON file (typically)
- e.g. MongoDb
- more structure than key-value store, easier to parse and query



```
{
    "customerid": "fc986e48ca6"
    "customer":
    {
    "firstname": "Pramod",
    "lastname": "Sadalage",
    "company": "ThoughtWorks",
    "likes": [ "Biking","Photography" ]
    }
    "billingaddress":
    { "state": "AK",
      "city": "DILLINGHAM",
      "type": "R"
     }
}
```

Figure 33: document-database

Column family

- columns stored together on disk, rather than rows, primarily for efficiency

- analysis becomes faster as less data is fetched
- automatic vertical partitioning
- related columns grouped into families
- e.g. Cassandra, BigTable

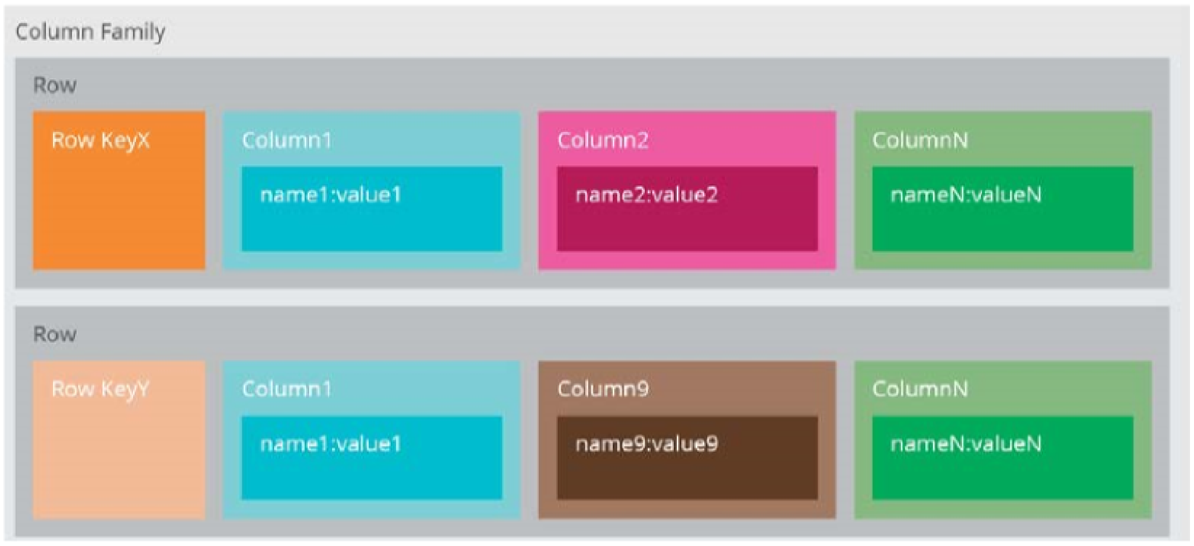


Figure 34: column-family

NoSQL Variants - Graph databases

- maintain information regarding relationships between data items
- nodes with properties
- e.g. friendship graph
- graphs are difficult to program in relational DB
- graph DB stores entities and their relationships
- graph queries deduce knowledge from the graph
- e.g. Neo4J

CAP Theorem

- CAP Theorem: you can only have 2 of consistency, partition tolerance, availability

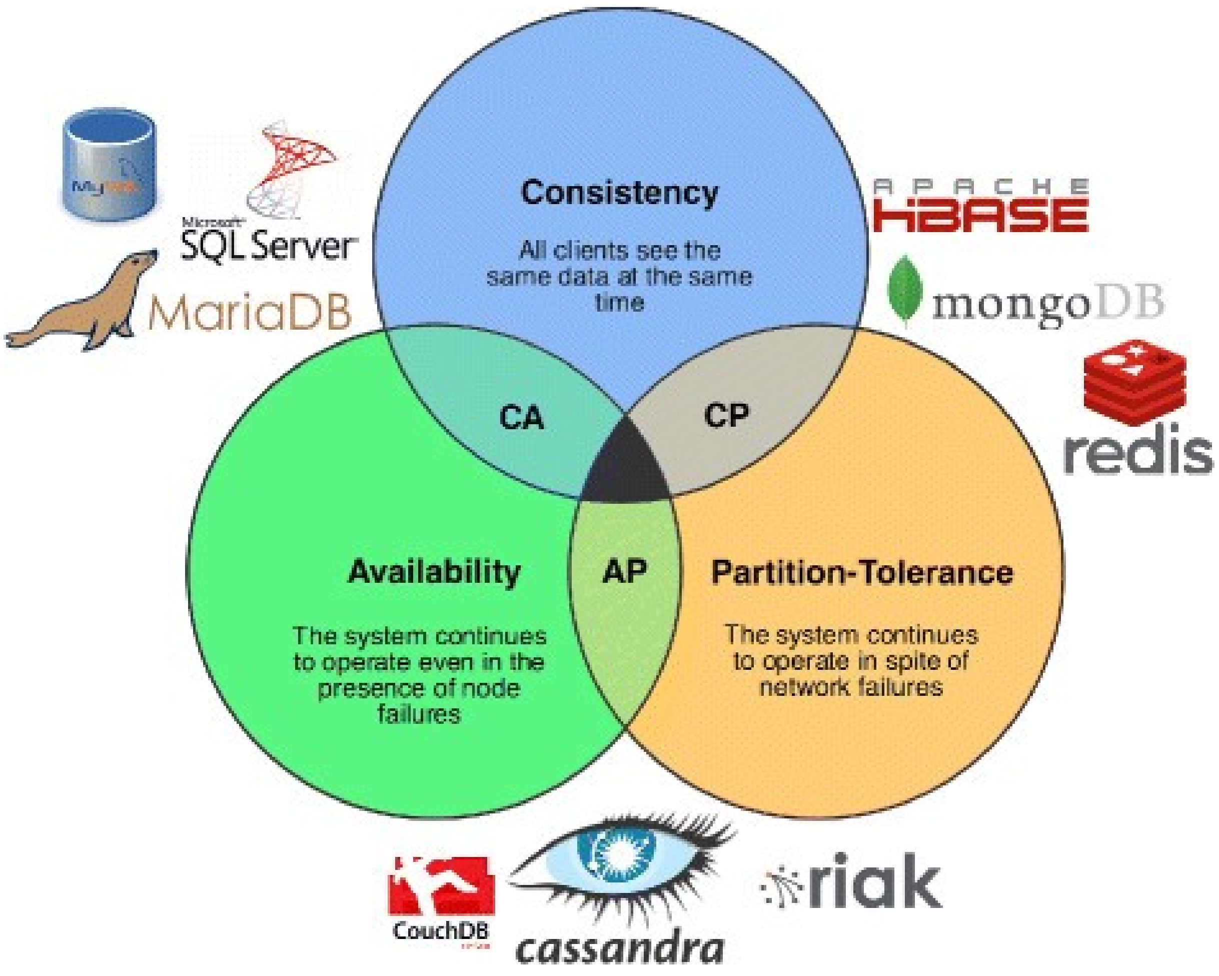

Consistency
All clients see the same data at the same time
CA
CP
AP
Availability
The system continues to operate even in the presence of node failures
Partition-Tolerance
The system continues to operate in spite of network failures
MySQL
Microsoft SQL Server
MariaDB
APACHE HBASE
mongoDB
redis
CouchDB
cassandra
riak

Figure 35: cap-theorem

- Fowler's version: if you have a distributed database, when a partition occurs, then choose between consistency OR availability

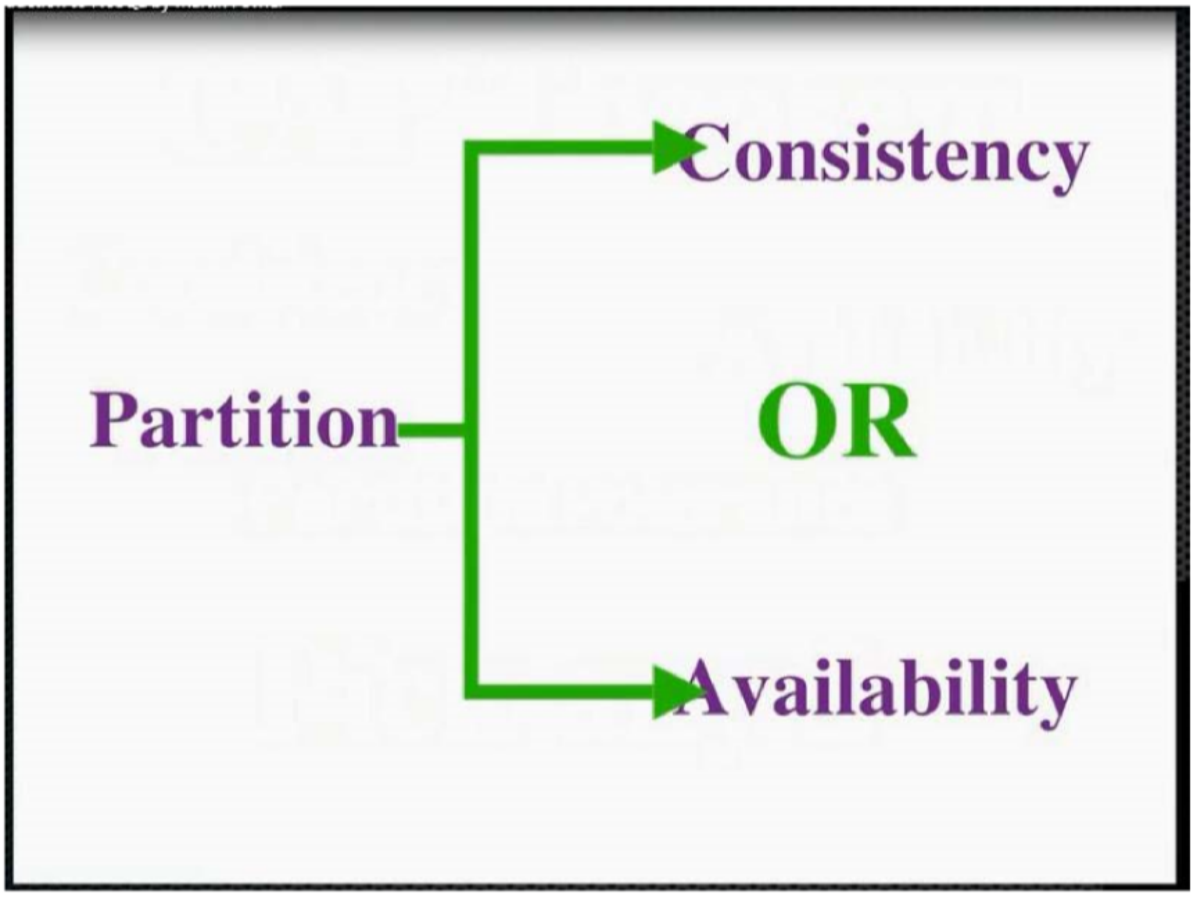


Figure 36: cap-theorem-2

ACID vs BASE

- ACID: Atomic, consistent, Isolated, Durable
- BASE: Basically available, Soft State, Eventual consistency
- **basically available**: requests will receive a response, but it may be inconsistent or changing
- **soft state**: state can change over time, even when there is no input there may be changes due to eventual consistency
- **eventual consistency**: system will eventually become consistent once it stops receiving input
  - data will propagate everywhere eventually but system continues to receive input and isn't checking consistency of every transaction before proceeding