Distributed Data Management

(Handout)

Dr. Eike Schallehn

Organization

Organization of Lecture and Exercises

- Weekly lecture
  - Teacher: Eike Schallehn (eike@iti.cs.uni-magdeburg.de)
- Weekly exercises with two alternative time slots
  - Starting in the third week of the lecture period
  - Teachers: Xiao Chen, Juliana Alves Pereira
- Written exam at the end of the semester (registration using HISQUIS system)

Prerequisites

- Required: knowledge about database basics from database introduction course
  - Basic principles, Relational Model, SQL, database design, ER Model
- Helpful: advanced knowledge about database internals
  - Query processing, storage structures
- Helpful hands-on experience:
  - SQL queries, DDL and DML

Content Overview

1. Foundations
2. Distributed DBMS: architectures, distribution, query processing, transaction management, replication
3. Parallel DBMS: architectures, query processing
4. Federated DBS: architectures, conflicts, integration, query processing
5. Peer-to-peer Data Management

English Literature /1

- M. Tamer Özsu, P. Valduriez: *Principles of Distributed Database Systems.* Second Edition, Prentice Hall, Upper Saddle River, NJ, 1999.
- S. Ceri and G. Pelagatti: *Distributed Databases Principles and Systems*, McGraw Hill Book Company, 1984.
- C. T. Yu, W. Meng: *Principles of Database Query Processing for Advanced Applications.* Morgan Kaufmann Publishers, San Francisco, CA, 1998.

English Literature /2

- Elmasri, R.; Navathe, S.: *Fundamentals of Database Systems*, Addison Wesley, 2003
- C. Dye: *Oracle Distributed Systems*, O'Reilly, Sebastopol, CA, 1999.
- D. Kossmann: *The State of the Art in Distributed Query Processing*, ACM Computing Surveys, Vol. 32, No. 4, 2000, S. 422-469.

German Literature

- E. Rahm, G. Saake, K.-U. Sattler: *Verteiltes und Paralleles Datenmanagement.* Springer-Verlag, Heidelberg, 2015.
- P. Dadam: *Verteilte Datenbanken und Client/Server-Systeme*, Springer-Verlag, Berlin, Heidelberg 1996.
- S. Conrad: *Föderierte Datenbanksysteme: Konzepte der Datenintegration.* Springer-Verlag, Berlin/Heidelberg, 1997.

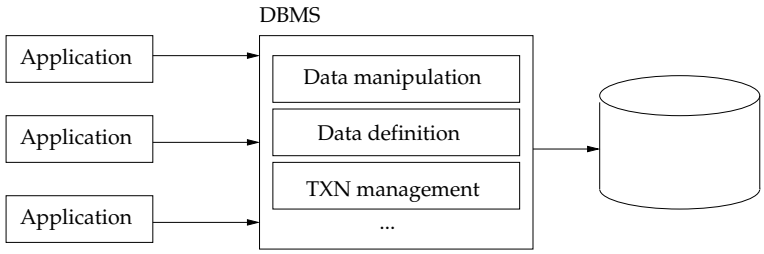
Part I
Introduction

Overview

Contents

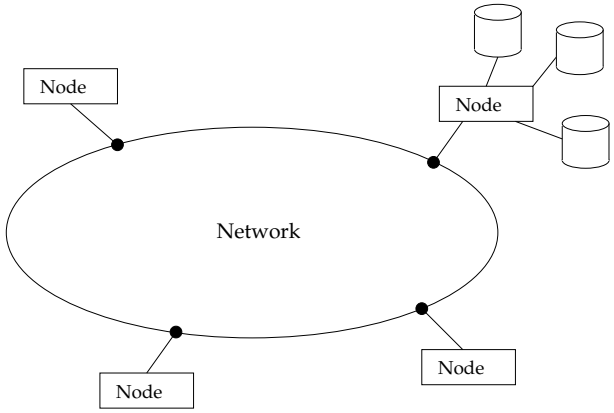
1 Motivation

Centralized Data Management

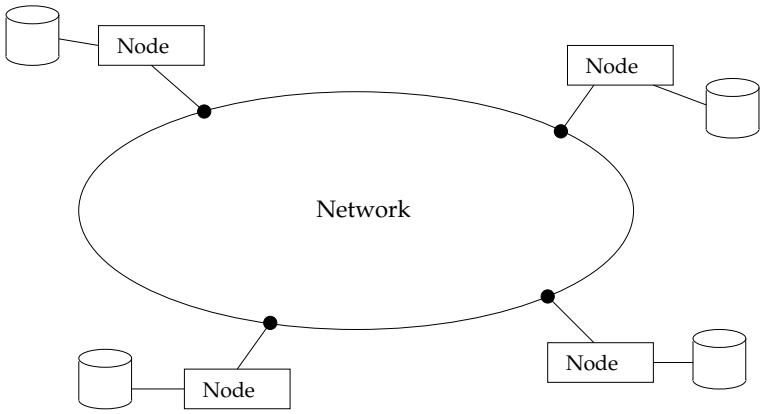


- New requirements
  - Support for de-centralized organization structures
  - High availability
  - High performance
  - Scalability

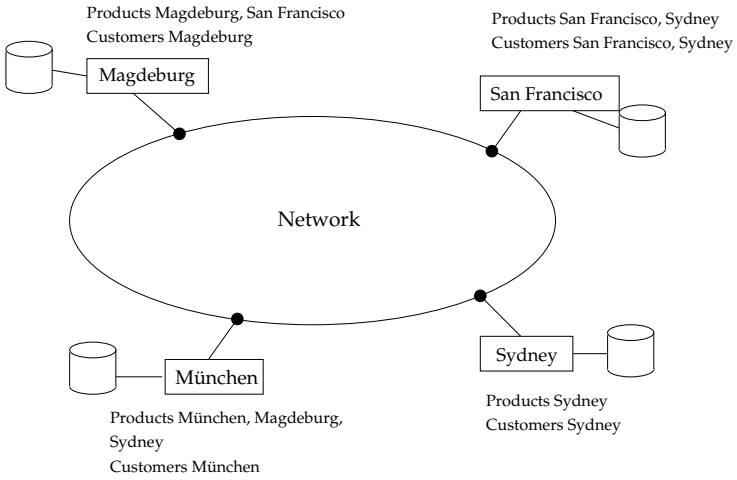
Client Server Data Management in a Network



Distributed Data Management



Distributed Data Management: Example



Advantages of Distributed DBMS

- Transparent management of distributed/replicated data
- Availability and fault tolerance
- Performance
- Scalability

Transparent Data Management

- Transparency: "'hide"' implementation details
- For (distributed) database systems
  - Data independence (physical, logical)
  - Network transparency
    - "'hide"' existence of the network
    - "'hide"' physical location of data
  - To applications a distributed DBS looks just like a centralized DBS

Transparent Data Management/2

- continued:
  - Replication transparency
    - Replication: managing copies of remote data (performance, availability, fault-tolerance)
    - Hiding the existence of copies (e.g. during updates)
  - Fragmentation transparency
    - Fragmentation: decomposition of relations and distribution of resulting fragments
    - Hiding decomposition of global relation

Who provides Transparency?

- Application
  - Different parts/modules of distributed application
  - Communication / data exchange using standard protocols (RPC, CORBA, HTTP, SOAP, ...)
- DBMS
  - Transparent SQL-access to data on remote DB-instances
  - Requires query decomposition, transaction coordination, replication
- Operating system
  - Operating systems provides network transparency e.g. on file system level (NFS) or through standard protocols (TCP/IP)

Fault-Tolerance

- Failure of one single node can be compensated
- Requires
  - Replicated copies on different nodes
  - Distributed transactions

Performance

- Data can be stored, where they are most likely used $\rightarrow$ reduction of transfer costs
- Parallel processing in distributed systems
  - Inter-transaction-parallelism: parallel processing of different transactions
  - Inter-query-parallelism: parallel processing of different queries
  - Intra-query-parallelism: parallel of one or several operations within one query

Scalability

- Requirements raised by growing databases or necessary performance improvement
  - Addition of new nodes/processors often cheaper than design of new system or complex tuning measures

Differentiation: Distributed Information System

- Distributed Information System
  - Application components communicate for purpose of data exchange (distribution on application level)
- Distributed DBS
  - Distribution solely realized on the DBS-level

Differentiation: Distributed File System

- Distributed File System provides non-local storage access by means of operating system
- DBMS on distributed file system
  - All data must be read from blocks stored on different disks
  - Processing is performed only within DBMS node (not distributed)
  - Distribution handled by operating system

Special Case: Parallel DBS

- Data management on simultaneous computer (multi processor, special hardware)
- Processing capacities are used for performance improvement
- Example
  - 100 GB relation, sequential read with 10 MB/s $\rightsquigarrow$ 17 minutes
  - parallel read on 10 nodes (without considering coordination overhead) $\rightsquigarrow$ 1:40 minutes

Special Case: Heterogeneous DBS

- Motivation: integration of previously existing DBS (legacy systems)
  - Integrated access: global queries, relationships between data objects in different databases, global integrity
- Problems
  - Heterogeneity on different levels: system, data model, schema, data
- Special importance on the WWW: integration of Web sources $\rightsquigarrow$ Mediator concept

Special Case: Peer-to-Peer-Systems

- Peer-to-Peer (P2P): networks without centralized servers
  - All / many nodes (peers) store data
  - Each node knows only some "‘close"’ neighbors
    - No global view
    - No centralized coordination
- Examples: Napster, Gnutella, Freenet, BitTorrent, ...
  - Distributed management of data (e.g. MP3-Files)
  - Lookup using centralized servers (Napster) or distributed (Gnutella)

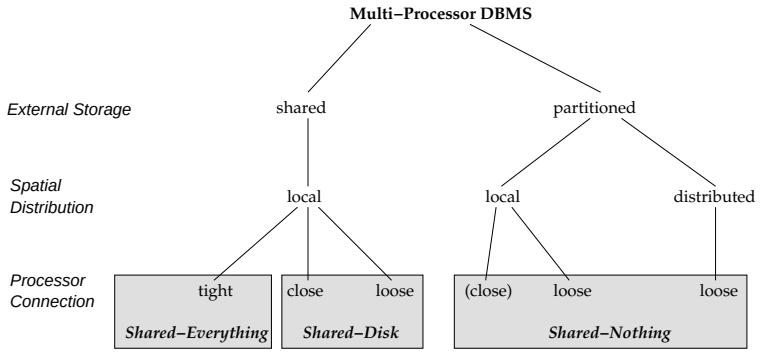
2 Classification of Multi-Processor DBMS

Multi-Processor DBMS

- In general: DBMS which are able to use multiple processors or DBMS-instances to process database operations [Rahm 94]
- Can be classified according to different criteria
  - Processors with same or different functionality
  - Access to external storage
  - Spatial distribution
  - Processor connection
  - Homogeneous vs. heterogeneous architecture

Classification Overview

- Assumption: each processor provides the same functionality
- Classification [Rahm94]



Criterion: Access to External Storage

- Partitioned access
  - External storage is divided among processors/nodes
    - Each processor has only access to local storage
    - Accessing different partitions requires communication
- Shared access
  - Each processor has access to full database
  - Requires synchronisation

Criterion: Spatial Distribution

- Locally distributed: DB-Cluster
  - Fast inter-processor communication
  - Fault-tolerance
  - Dynamic load balancing possible
  - Little administration efforts
  - Application: parallel DBMS, solutions for high availabilty
- Remotely distributed: distributed DBS in WAN scenarios
  - Support for distributed organization structures
  - Fault-tolerant (even to major catastrophes)
  - Application: distributed DBS

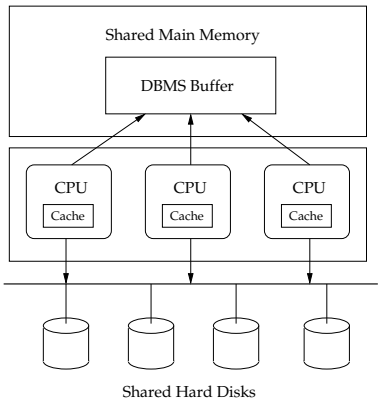
Criterion: Processor Connection

- Tight connection
  - Processors share main memory
  - Efficient co-operation
  - Load-balancing by means of operating system
  - Problems: Fault-tolerance, cache coherence, limited number of processors (≤ 20)
  - Parallel multi-processor DBMS

Criterion: Processor Connection /2

- Loose connection:
  - Independent nodes with own main memory and DBMS instances
  - Advantages: failure isolation, scalability
  - Problems: expensive network communication, costly DB operations, load balancing
- Close connection:
  - Mix of the above
  - In addition to own main memory there is connection via shared memory
  - Managed by operating system

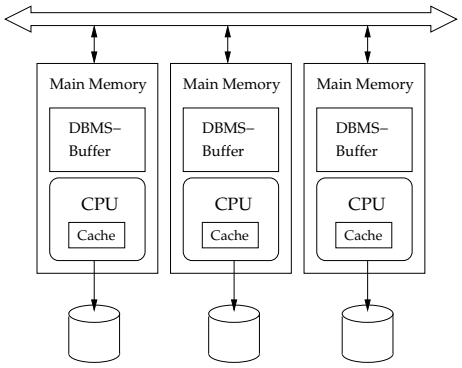
Class: Shared-Everything



Class: Shared-Everything /2

- Simple realization of DBMS
- Distribution transparency provided by operating system
- Expensive synchronization
- Extended implementation of query processing

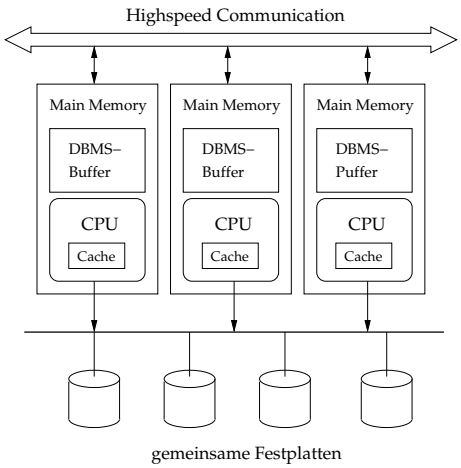
Class: Shared-Nothing



Class: Shared-Nothing /2

- Distribution of DB across various nodes
- Distributed/parallel execution plans
- TXN management across participating nodes
- Management of catalog and replicas

Class: Shared-Disk



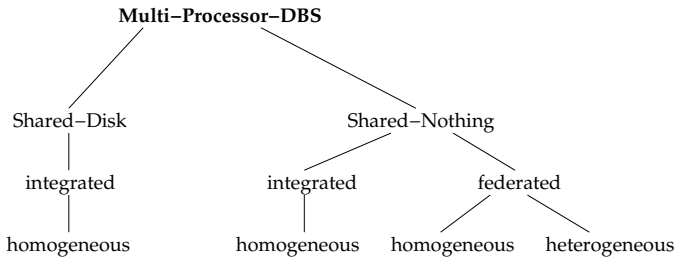
Class: Shared-Disk /2

- Avoids physical data distribution
- No distributed TXNs and query processing
- Requires buffer invalidation

Criterion: Integrated vs. Federated DBS

- Integrated:
  - Shared database for all nodes $\rightsquigarrow$ one conceptual schema
  - High distribution transparency: access to distributed DB via local DBMS
  - Requires co-operation of DBMS nodes $\rightsquigarrow$ restricted autonomy
- Federated:
  - Nodes with own DB and own conceptual schema
  - Requires schema integration $\rightsquigarrow$ global conceptual schema
  - High degree of autonomy of nodes

Criterion: Integrated vs. Federates DBS /2



Criterion: Centralized vs. De-centralized Coordination

- Centralized:
  - Each node has global view on database (directly of via master)
  - Central coordinator: initiator of query/transaction $\rightarrow$ knows all participating nodes
  - Provides typical DBS properties (ACID, result completeness, etc.)
  - Applications: distributed and parallel DBS
    - Limited availability, fault-tolerance, scalabilty

Criterion: Centralized vs. De-centralized Coordination /2

- De-centralized:
  - No global view on schema $\rightarrow$ peer knows only neighbors
  - Autonomous peers; global behavior depends on local interaction
  - Can not provide typical DBMS properties
  - Application: P2P systems
    - Advantages: availability, fault-tolerance, scalabilty

Comparison

	Parallel DBS	Distributed DBS	Federated DBS
High TXN rates	↑	→↗	→
Intra-TXN-Parallelism	↑	→↗	↘→
Scalability	↗	→↗	→
Availability	↗	↗	↘
Geogr. Distribution	↘	↗	↗
Node Autonomy	↘	→	↗
DBS-Heterogeneity	↘	↘	↗
Administration	→	↘	↘↓

3 Recapitulation

Database Management Systems (DBMS)

- Nowadays commonly used
  - to store huge amounts of data persistently,
  - in collaborative scenarios,
  - to fulfill high performance requirements,
  - to fulfill high consistency requirements,
  - as a basic component of information systems,
  - to serve as a common IT infrastructure for departments of an organization or company.

Database Management Systems

A **database management system (DBMS)** is a suite of computer programs designed to manage a database and run operations on the data requested by numerous clients.

A **database (DB)** is an organized collection of data.

A **database system (DBS)** is the concrete instance of a database managed by a database management system.

Codd's 9 Rules for DBMS

- Differentiate DBMS from other systems managing data persistently, e.g. file systems

1 **Integration:** homogeneous, non-redundant management of data

2 **Operations:** means for accessing, creating, modifying, and deleting data

3 **Catalog:** the data description must be accessible as part of the database itself

4 **User views:** different users/applications must be able to have a different perception of the data

5 **Integrity control:** the systems must provide means to grant the consistency of data

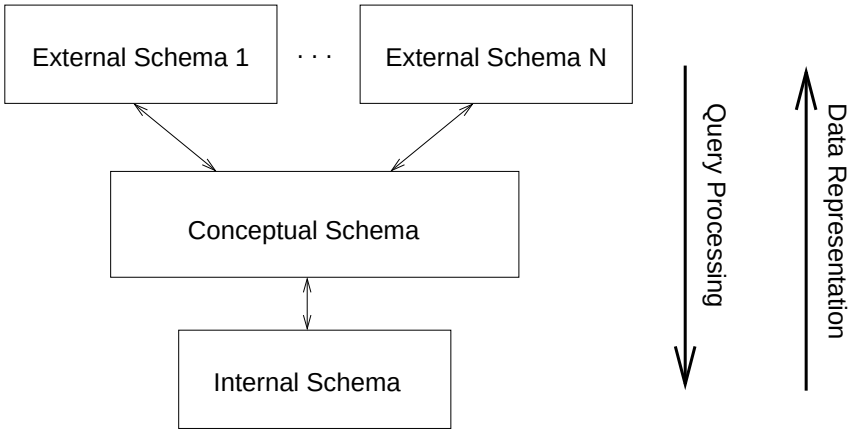
6 **Data security:** the system must grant only authorized accesses

7 **Transactions:** multiple operations on data can be grouped into a logical unit

8 **Synchronization:** parallel accesses to the database are managed by the system

9 **Data backups:** the system provides functionality to grant long-term accessibility even in case of failures

3 Level Schema Architecture



- Important concept of DBMS
- Provides
  - transparency, i.e. non-visibility, of storage implementation details
  - ease of use
  - decreased application maintenance efforts
  - conceptual foundation for standards
  - portability
- Describes abstraction steps:
  - Logical data independence
  - Physical data independence

Data Independence

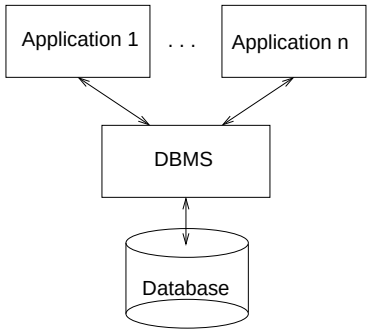
Logical data independence: Changes to the logical schema level must not require a change to an application (external schema) based on the structure.

Physical data independence: Changes to the physical schema level (how data is stored) must not require a change to the logical schema.

Architecture of a DBS

Schema architecture roughly conforms to general architecture of a database systems

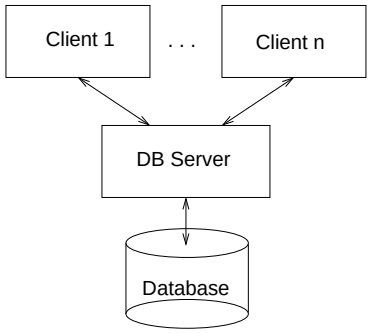
- **Applications** access database using specific **views (external schema)**
- The **DBMS** provides access for all applications using the **logical schema**
- The **database** is stored on secondary storage according to an **internal schema**



Client Server Architecture

Schema architecture does not directly relate to client server architecture (communication/network architecture)

- Clients may run several applications
- Applications may run on several clients
- DB servers may be distributed
- ...

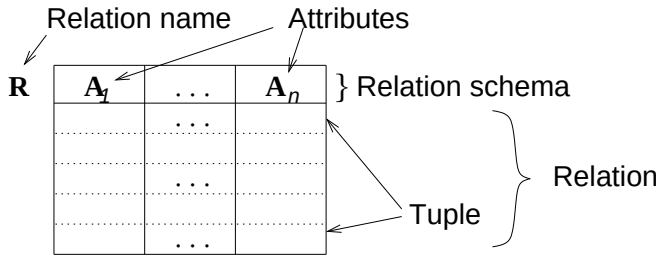


The Relational Model

- Developed by Edgar F. Codd (1923-2003) in 1970
- Derived from mathematical model of n-ary relations
- Colloquial: data is organized as tables (relations) of records (n-tuples) with columns (attributes)
- Currently most commonly used database model
- Relational Database Management Systems (RDBMS)
- First prototype: IBM System R in 1974
- Implemented as core of all major DBMS since late '70s: IBM DB2, Oracle, MS SQL Server, Informix, Sybase, MySQL, PostgreSQL, etc.
- Database model of the DBMS language standard SQL

Basic Constructs

A **relational database** is a database that is structured according to the relational database model. It consists of a set of relations.



Integrity Constraints

- Static integrity constraints describe valid tuples of a relation
  - Primary key constraint
  - Foreign key constraint (referential integrity)
  - Value range constraints
  - ...
- In SQL additionally: uniqueness and not-NULL
- Transitional integrity constraints describe valid changes to a database

The Relational Algebra

A **relational algebra** is a set of operations that are closed over relations.

- Each operation has one or more relations as input
- The output of each operation is a relation

Relational Operations

Primitive operations:

- Selection σ
- Projection π
- Cartesian product (cross product) $\times$
- Set union $\cup$
- Set difference $-$
- Rename β

Non-primitive operations

- Natural Join $\bowtie$
- θ-Join and Equi-Join $\bowtie_{\varphi}$
- Semi-Join $\ltimes$
- Outer-Joins $= \times$
- Set intersection $\cap$
- $\ldots$

Notation for Relations and Tuples

- If R denotes a relation schema (set of attributes), than the function $r(R)$ denotes a relation conforming to that schema (set of tuples)
- R and $r(R)$ are often erroneously used synonymously to denote a relation, assuming that for a given relation schema only one relation exists
- $t(R)$ denotes a tuple conforming to a relation schema
- $t(R.a)$ denotes an attribute value of a tuple for an attribute $a \in R$

The Selection Operation σ

Select tuples based on predicate or complex condition

PROJECT			
PNAME	**PNUMBER**	**PLOCATION**	**DNUM**
ProductX	1	Bellaire	5
ProductY	2	Sugarland	5
ProductZ	3	Houston	5
Computerization	10	Stafford	4
Reorganization	20	Houston	1
Newbenefits	30	Stafford	4

$$\sigma_{PLOCATION='Stafford'}(r(PROJECT))$$

PNAME	**PNUMBER**	**PLOCATION**	**DNUM**
Computerization	10	Stafford	4
Newbenefits	30	Stafford	4

The Projection Operation π

Project to set of attributes - remove duplicates if necessary

PROJECT			
PNAME	**PNUMBER**	**PLOCATION**	**DNUM**
ProductX	1	Bellaire	5
ProductY	2	Sugarland	5
ProductZ	3	Houston	5
Computerization	10	Stafford	4
Reorganization	20	Houston	1
Newbenefits	30	Stafford	4

$$\pi_{PLOCATION,DNUM}(r(PROJECT))$$

PLOCATION	DNUM
Bellaire	5
Sugarland	5
Houston	5
Stafford	4
Houston	1

Cartesian or cross product $\times$

Create all possible combinations of tuples from the two input relations

R	
A	**B**
1	2
3	4

S		
C	**D**	**E**
5	6	7
8	9	10
11	12	13

$$r(R) \times r(S)$$

A	B	C	D	E
1	2	5	6	7
1	2	8	9	10
1	2	11	12	13
3	4	5	6	7
3	4	8	9	10
3	4	11	12	13

Set: Union, Intersection, Difference

- All require compatible schemas: attribute names and domains
- Union: duplicate entries are removed
- Intersection and Difference: $\emptyset$ as possible result

The Natural Join Operation $\bowtie$

- Combine tuples from two relations $r(R)$ and $r(S)$ where for
  - all attributes $a = R \cap S$ (defined in both relations)

- is $t(R.a) = t(S.a)$.

- Basic operation for following key relationships
- If there are no common attributes result is Cartesian product $R \cap S = \emptyset \implies r(R) \bowtie r(S) = r(R) \times r(S)$
- Can be expressed as combination of π, σ and $\times$ $r(R) \bowtie r(S) = \pi_{R \cup S}(\sigma_{\bigwedge_{a \in R \cap S} t(R.a)=t(S.a)}(r(R) \times r(S)))$

The Natural Join Operation $\bowtie$ /2

R	
A	**B**
1	2
3	4
5	6

S		
B	**C**	**D**
4	5	6
6	7	8
8	9	10

$r(R) \bowtie r(S)$

A	B	C	D
3	4	5	6
5	6	7	8

The Semi-Join Operation $\ltimes$

- Results all tuples from one relation having a (natural) join partner in the other relation $r(R) \ltimes r(S) = \pi_R(r(R) \bowtie r(S))$

PERSON	
PID	**NAME**
1273	Dylan
2244	Cohen
3456	Reed

CAR	
PID	**BRAND**
1273	Cadillac
1273	VW Beetle
3456	Stutz Bearcat

$r(PERSON) \ltimes r(CAR)$

PID	NAME
1273	Dylan
3456	Reed

Other Join Operations

- **Conditional join:** join condition φ is explicitly specified $r(R) \bowtie_\varphi r(S) = \sigma_\varphi(r(R) \times r(S))$
- **θ-Join:** special conditional join, where φ is a single predicate of the form $a \theta b$ with $a \in R$, $b \in S$, and $\theta \in \{=, \neq, >, <, \leq, \geq, \dots\}$

- **Equi-Join:** special θ-Join where θ is $=$.
- **(Left or Right) Outer Join:** union of natural join result and tuples from the left or right input relation which could not be joined (requires NULL-values to grant compatible schemas).

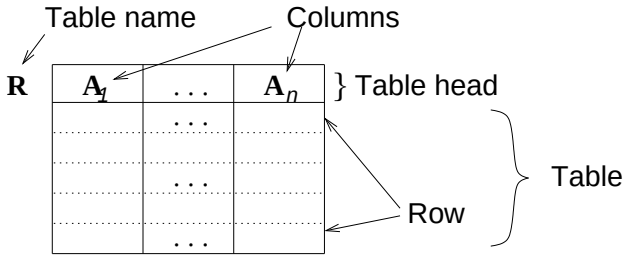
Relational Database Management Systems

A **Relational Database Management System (RDBMS)** is a database management system implementing the relational database model.

- Today, most relational DBMS implement the SQL database model
- There are some significant differences between the relational model and SQL (duplicate rows, tuple order significant, anonymous column names, etc.)
- Most distributed and parallel DBMS have a relational (SQL) data model

SQL Data Model

- Said to implement relational database model
- Defines own terms



- Some significant differences exist

Structured Query Language

- **Structured Query Language (SQL):** declarative language to describe requested query results
- Realizes relational operations (with the mentioned discrepancies)
- Basic form: `SELECT-FROM-WHERE`-block (SFW)

```
SELECT FNAME, LNAME, MGRSTARTDATE
FROM EMPLOYEE, DEPARTMENT
WHERE SSN=MGRSSN
```

SQL: Selection σ

$\sigma_{DNO=5 \wedge SALARY>30000}(r(EMPLOYEE))$

```
SELECT *
FROM EMPLOYEE
WHERE DNO=5 AND SALARY>30000
```

SQL: Projection π

$\pi_{LNAME,FNAME}(r(EMPLOYEE))$

```
SELECT LNAME,FNAME
FROM EMPLOYEE
```

- Difference to RM: does not remove duplicates
- Requires additional `DISTINCT`

```
SELECT DISTINCT LNAME,FNAME
FROM EMPLOYEE
```

SQL: Cartesian Product $\times$

$r(EMPLOYEE) \times r(PROJECT)$

```
SELECT *
FROM EMPLOYEE, PROJECT
```

SQL: Natural Join $\bowtie$

$r(DEPARTMENT) \bowtie r(DEPARTMENT\_LOCATIONS)$

```
SELECT *
FROM DEPARTMENT
     NATURAL JOIN DEPARTMEN_LOCATIONS
```

SQL: Equi-Join

$r(EMPLOYEE) \bowtie_{SSN=MGRSSN} r(DEPARTMENT)$

```
SELECT *
FROM EMPLOYEE, DEPARTMENT
WHERE SSN=MGRSSN
```

SQL: Union

$r(R) \cup r(S)$

```
SELECT * FROM R
UNION
SELECT * FROM S
```

- Other set operations: `INTERSECT`, `MINUS`
- Does remove duplicates (in compliance with RM)
- If duplicates required:

```
SELECT * FROM R
UNION ALL
SELECT * FROM S
```

SQL: Other Features

- SQL provides several features not in the relational algebra
  - Grouping And Aggregation Functions, e.g. `SUM`, `AVG`, `COUNT`, ...
  - Sorting

```
SELECT PLOCATION, AVG(HOURS)
FROM EMPLOYEE, WORKS_ON, PROJECT
WHERE SSN=ESSN AND PNO=PNUMBER
GROUP BY PLOCATION
HAVING COUNT(*) > 1
ORDER BY PLOCATION
```

SQL DDL

- **Data Definition Language** to create, modify, and delete schema objects

```
CREATE DROP ALTER TABLE mytable ( id INT, ...)
DROP TABLE ...
ALTER TABLE ...
CREATE VIEW myview AS SELECT ...
DROP VIEW ...
CREATE INDEX ...
DROP INDEX ...
...
```

Simple Integrity Constraints

```
CREATE TABLE employee(
    ssn INTEGER,
    lname VARCHAR2(20) NOT NULL,
    dno INTEGER,
    ...
    FOREIGN KEY (dno)
        REFERENCES department(dnumber),
    PRIMARY KEY (ssn)
)
```

- Additionally: triggers, explicit value domains, ...

SQL DML

- **Data Manipulation Language** to create, modify, and delete tuples

```
INSERT INTO (<COLUMNS>) mytable VALUES (...)

INSERT INTO (<COLUMNS>) mytable SELECT ...

UPDATE mytable
SET ...
WHERE ...

DELETE FROM mytable
WHERE ...
```

Other Parts of SQL

- Data Control Language (DCL): `GRANT, REVOKE`
- Transaction management: `START TRANSACTION, COMMIT, ROLLBACK`
- Stored procedures and imperative programming concepts
- Cursor definition and management

Transactions

- Sequence of database operations
  - Read and write operations
  - In SQL sequence of INSERT, UPDATE, DELETE, SELECT statements
- Build a semantic unit, e.g. transfer of an amount from one bank account to another
- Has to conform to **ACID** properties

Transactions: ACID Properties

- **A**tomicity means that a transaction can not be interrupted or performed only partially
  - TXN is performed in its entirety or not at all
- **C**onsistency to preserve data integrity
  - A TXN starts from a consistent database state and ends with a consistent database state

- **I**solation
  - Result of a TXN must be independent of other possibly running parallel TXNs
- **D**urability or persistence
  - After a TXN finished successfully (from the user's view) its results must be in the database and the effect can not be reversed

Functional Dependencies

- A functional dependency (FD) $X \to Y$ within a relation between sets $r(R)$ of attributes $X \subseteq R$ and $Y \subseteq R$ exists, if for each tuple the values of X determine the values for Y
- i.e.

$$\forall t_1, t_2 \in r(R) : t_1(X) = t_2(X) \Rightarrow t_1(Y) = t_2(Y)$$

Derivation Rules for FDs

R_1	Reflexivity	if $X \supseteq Y$	$\implies X \to Y$
R_2	Accumulation	$\{X \to Y\}$	$\implies XZ \to YZ$
R_3	Transitivity	$\{X \to Y, Y \to Z\}$	$\implies X \to Z$
R_4	Decomposition	$\{X \to YZ\}$	$\implies X \to Y$
R_5	Unification	$\{X \to Y, X \to Z\}$	$\implies X \to YZ$
R_6	Pseudotransitivity	$\{X \to Y, WY \to Z\}$	$\implies WX \to Z$

R_1-R_3 known as *Armstrong-Axioms* (sound, complete)

Normal Forms

- Formal criteria to force schemas to be free of redundancy
- First Normal Form (1NF) allows only *atomic attribute values*
  - i.e. all attribute values ar of basic data types like `integer` or `string` but not further structured like e.g. an `array` or a `set` of values
- Second Normal Form (2NF) avoids *partial dependencies*
  - A partial dependency exist, if a non-key attribute is functionally dependent on a real subset of the primary key of the relation

Normal Forms /2

- Third Normal Form (3NF) avoids *transitive dependencies*
  - Disallows functional dependencies between non-key attributes
- Boyce-Codd-Normal Form (BCNF) disallows *transitive dependencies* also for primary key attributes