CHAPTER 2

Database System Concepts and Architecture
Outline

- Data Models and Their Categories
- History of Data Models
- Schemas, Instances, and States
- Three-Schema Architecture
- Data Independence
- DBMS Languages and Interfaces
- Database System Utilities and Tools
- Centralized and Client-Server Architectures
- Classification of DBMSs
Data Models

- **Data Model:**
  - A set of concepts to describe the **structure** of a database, the **operations** for manipulating these structures, and certain **constraints** that the database should obey.
  - Provides means to achieve **data abstraction**

- **Data Model Structure and Constraints:**
  - **Constructs** are used to define the database structure
  - Constructs typically include **elements** (and their **data types**) as well as groups of elements (e.g. **entity**, **record**, **table**), and **relationships** among such groups
  - **Constraints** specify some **restrictions** on valid data; these constraints must be enforced at all times
Data Models (continued)

- **Data Model Operations:**
  - These operations are used for specifying database *retrievals* and *updates* by referring to the constructs of the data model.
  - Operations on the data model may include *basic model operations* (e.g. generic insert, delete, update) and *user-defined operations* (e.g. compute_student_gpa, update_inventory)
Categories of Data Models

- **Conceptual (high-level, semantic) data models:**
  - Provide concepts that are close to the way many users perceive data.
  - (Also called *entity-based* or *object-based* data models.)

- **Physical (low-level, internal) data models:**
  - Provide concepts that describe details of how data is stored in the computer. These are usually specified in an ad-hoc manner through DBMS design and administration manuals.

- **Implementation (representational) data models:**
  - Provide concepts that fall between the above two, used by many commercial DBMS implementations (e.g. relational data models used in many commercial systems).

- **Self-Describing Data Models:**
  - Combine the description of data with the data values. Examples include XML, key-value stores and some NOSQL systems.
Schemas versus Instances

- **Database Schema:**
  - The *description* of a database.
  - Includes descriptions of the database structure, data types, and the constraints on the database.

- **Schema Diagram:**
  - An *illustrative* display of (most aspects of) a database schema.

- **Schema Construct:**
  - A *component* of the schema or an object within the schema, e.g., STUDENT, COURSE.
Schemas versus Instances

- **Database State:**
  - The actual data stored in a database at a **particular moment in time**. This includes the collection of all the data in the database.
  - Also called database **instance** (or occurrence or snapshot).

  - The term **instance** is also applied to individual database components, e.g. **record instance**, **table instance**, **entity instance**
Database Schema vs. Database State

- **Database State:**
  - Refers to the *content* of a database at a moment in time.

- **Initial Database State:**
  - Refers to the database state when it is initially loaded into the system.

- **Valid State:**
  - A state that satisfies the *structure* and *constraints* of the database.
Database Schema vs. Database State (continued)

- Distinction
  - The *database schema* changes very infrequently.
  - The *database state* changes every time the database is updated.

- Schema is also called *intension*.
- State is also called *extension*. 
Example of a Database Schema

**STUDENT**

<table>
<thead>
<tr>
<th>Name</th>
<th>Student_number</th>
<th>Class</th>
<th>Major</th>
</tr>
</thead>
</table>

**COURSE**

<table>
<thead>
<tr>
<th>Course_name</th>
<th>Course_number</th>
<th>Credit_hours</th>
<th>Department</th>
</tr>
</thead>
</table>

**PREREQUISITE**

<table>
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<tr>
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<th>Prerequisite_number</th>
</tr>
</thead>
</table>

**SECTION**

<table>
<thead>
<tr>
<th>Section_identifier</th>
<th>Course_number</th>
<th>Semester</th>
<th>Year</th>
<th>Instructor</th>
</tr>
</thead>
</table>

**GRADE_REPORT**

<table>
<thead>
<tr>
<th>Student_number</th>
<th>Section_identifier</th>
<th>Grade</th>
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</thead>
</table>

*Figure 2.1*

Schema diagram for the database in Figure 1.2.
### Example of a database state

#### COURSE

<table>
<thead>
<tr>
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<th>Department</th>
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<tbody>
<tr>
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<td>CS</td>
</tr>
<tr>
<td>Data Structures</td>
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<td>4</td>
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<tr>
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<td>MATH</td>
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<tr>
<td>Database</td>
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<td>3</td>
<td>CS</td>
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#### SECTION

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<th>Instructor</th>
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<td>Fall</td>
<td>04</td>
<td>King</td>
</tr>
<tr>
<td>92</td>
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<td>Fall</td>
<td>04</td>
<td>Anderson</td>
</tr>
<tr>
<td>102</td>
<td>CS3320</td>
<td>Spring</td>
<td>05</td>
<td>Knuth</td>
</tr>
<tr>
<td>112</td>
<td>MATH2410</td>
<td>Fall</td>
<td>05</td>
<td>Chang</td>
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<td>135</td>
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#### GRADE REPORT

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<tr>
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<td>A</td>
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<tr>
<td>8</td>
<td>102</td>
<td>B</td>
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<tr>
<td>8</td>
<td>135</td>
<td>A</td>
</tr>
</tbody>
</table>

#### PREREQUISITE

<table>
<thead>
<tr>
<th>Course_number</th>
<th>Prerequisite_number</th>
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<tbody>
<tr>
<td>CS3380</td>
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<td>CS3380</td>
<td>MATH2410</td>
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<tr>
<td>CS3320</td>
<td>CS1310</td>
</tr>
</tbody>
</table>

*Figure 1.2* A database that stores student and course information.
Three-Schema Architecture

- Proposed to support DBMS characteristics of:
  - Program-data independence.
  - Support of multiple views of the data.
- Not explicitly used in commercial DBMS products, but has been useful in explaining database system organization.
Three-Schema Architecture

- Defines DBMS schemas at three levels:
  - **Internal schema** at the internal level to describe physical storage structures and access paths (e.g., indexes).
    - Typically uses a physical data model.
  - **Conceptual schema** at the conceptual level to describe the structure and constraints for the whole database for a community of users.
    - Uses a conceptual or an implementation data model.
  - **External schemas** at the external level to describe the various user views.
    - Usually uses the same data model as the conceptual schema.
The three-schema architecture

**Figure 2.2**
The three-schema architecture.

- **External Level**
  - External/Conceptual Mapping

- **Conceptual Level**
  - Conceptual/Internal Mapping

- **Internal Level**

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  End Users
     /\                /\                /\
   /   \              /   \              /   \
  \     \            \     \            \     \
   \  End Users       \  External       \  External View
                    View
     /\                /\                /\
   /   \              /   \              /   \
  \     \            \     \            \     \
   \   Conceptual    \   Conceptual    \   Conceptual Schema
     Schema
     /\                /\                /\
   /   \              /   \              /   \
  \     \            \     \            \     \
   \  Internal       \  Internal       \  Internal Schema
           Schema
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Three-Schema Architecture

- **Mappings** among schema levels are needed to transform requests and data.
  - Programs refer to an external schema, and are mapped by the DBMS to the internal schema for execution.
  - Data extracted from the internal DBMS level is reformatted to match the user’s external view (e.g. formatting the results of an SQL query for display in a Web page)
Data Independence

- **Logical Data Independence:**
  - The capacity to change the conceptual schema without having to change the external schemas and their associated application programs.

- **Physical Data Independence:**
  - The capacity to change the internal schema without having to change the conceptual schema.
  - For example, the internal schema may be changed when certain file structures are reorganized or new indexes are created to improve database performance.
Data Independence (continued)

- When a **schema at a lower level is changed**, only the **mappings** between this schema and higher-level schemas need to be changed in a DBMS that fully supports **data independence**.

- The **higher-level schemas** themselves are **unchanged**.
  - Hence, the **application programs** need not be changed since they refer to the external schemas.
DBMS Languages

- Data Definition Language (DDL)
- Data Manipulation Language (DML)
  - High-Level or Non-procedural Languages: These include the relational language SQL
    - May be used in a standalone way or may be embedded in a programming language
  - Low Level or Procedural Languages:
    - These must be embedded in a programming language
DBMS Languages

- **Data Definition Language (DDL):**
  - Used by the DBA and database designers to specify the conceptual schema of a database.
  - In many DBMSs, the DDL is also used to define internal and external schemas (views).
  - In some DBMSs, separate storage definition language (SDL) and view definition language (VDL) are used to define internal and external schemas.
    - SDL is typically realized via DBMS commands provided to the DBA and database designers.
DBMS Languages

- **Data Manipulation Language (DML):**
  - Used to specify database **retrievals** and **updates**
  - DML commands (data sublanguage) can be *embedded* in a general-purpose programming language (host language), such as COBOL, C, C++, or Java.
  - A library of functions can also be provided to access the DBMS from a programming language
  - Alternatively, stand-alone DML commands can be applied directly (called a **query language**).
Types of DML

- **High Level or Non-procedural Language:**
  - For example, the SQL relational language
  - Are “set”-oriented and specify what data to retrieve rather than how to retrieve it.
  - Also called **declarative languages**.

- **Low Level or Procedural Language:**
  - Retrieve data one record-at-a-time;
  - Constructs such as looping are needed to retrieve multiple records, along with positioning pointers.
DBMS Interfaces

- **Stand-alone query language interfaces**
  - Example: Entering SQL queries at the **DBMS interactive SQL interface** (e.g. SQL*Plus in ORACLE)

- **Programmer interfaces** for embedding DML in programming languages

- **User-friendly interfaces**
  - Menu-based, forms-based, graphics-based, etc.

- **Mobile Interfaces**: interfaces allowing users to perform transactions using mobile apps
DBMS Programming Language Interfaces

- Programmer interfaces for embedding DML in a programming languages:
  - **Embedded Approach**: e.g. embedded SQL (for C, C++, etc.), SQLJ (for Java)
  - **Procedure Call Approach**: e.g. JDBC for Java, ODBC (Open Database Connectivity) for other programming languages as API’s (application programming interfaces)
  - **Database Programming Language Approach**: e.g. ORACLE has PL/SQL, a programming language based on SQL; language incorporates SQL and its data types as integral components
  - **Scripting Languages**: PHP (client-side scripting) and Python (server-side scripting) are used to write database programs.
User-Friendly DBMS Interfaces

- Menu-based (Web-based), popular for browsing on the web
- Forms-based, designed for naïve users used to filling in entries on a form
- Graphics-based
  - Point and Click, Drag and Drop, etc.
  - Specifying a query on a schema diagram
- Natural language: requests in written English
- Combinations of the above:
  - For example, both menus and forms used extensively in Web database interfaces
Other DBMS Interfaces

- Natural language: free text as a query
- Speech: Input query and Output response
- Web Browser with keyword search
- Parametric interfaces, e.g., bank tellers using function keys.

Interfaces for the DBA:
- Creating user accounts, granting authorizations
- Setting system parameters
- Changing schemas or access paths
The Database System Environment

- DBMS component modules
  - DDL compiler
  - Interactive query interface
    - Query compiler
    - Query optimizer
  - Precompiler
  - DML compiler
The Database System Environment (cont'd.)

- **DBMS component modules**
  - Buffer management
  - Stored data manager
  - Runtime database processor
  - System catalog
  - Concurrency control system
  - Backup and recovery system
Typical DBMS Component Modules

Figure 2.3
Component modules of a DBMS and their interactions.
Typical DBMS Component Modules

![Diagram of DBMS component modules and their interactions.]

**Figure 2.3**
Component modules of a DBMS and their interactions.
Database System Utilities

To perform certain functions such as:

- **Loading data** stored in files into a database. Includes data conversion tools.
- **Backing up** the database periodically on tape.
- **Reorganizing database file structures**.
- **Performance monitoring** utilities.
- **Report generation** utilities.
- Other functions, such as **sorting**, **user monitoring**, **data compression**, etc.
Other Tools

- **Data dictionary / repository:**
  - Used to store schema descriptions and other information such as design decisions, application program descriptions, user information, usage standards, etc.
  - **Active data dictionary** is accessed by DBMS software and users/DBA.
  - **Passive data dictionary** is accessed by users/DBA only.
Other Tools

- Application Development Environments and CASE (computer-aided software engineering) tools:

- Examples:
  - PowerBuilder (Sybase)
  - JBuilder (Borland)
  - JDeveloper 10G (Oracle)
Centralized and Client-Server DBMS Architectures

- Centralized DBMS:
  - Combines everything into single system including DBMS software, hardware, application programs, and user interface processing software.
  - User can still connect through a remote terminal – however, all processing is done at centralized site.
A Physical Centralized Architecture

- **Terminals**
  - Display Monitor
  - ... Display Monitors
  - Network

- **Software**
  - Application Programs
  - Terminal Display Control
  - Text Editors
  - DBMS
  - Compilers

- **Operating System**
  - System Bus
  - Controller
  - Controller
  - Controller

- **Hardware/Firmware**
  - CPU
  - Memory
  - Disk
  - I/O Devices (Printers, Tape Drives, ...)

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Figure 2.4
A physical centralized architecture.
Basic 2-tier Client-Server Architectures

- Specialized Servers with Specialized functions
  - Print server
  - File server
  - DBMS server
  - Web server
  - Email server
- Clients can access the specialized servers as needed
Logical two-tier client server architecture

**Figure 2.5** Logical two-tier client/server architecture.

**Figure 2.6** Physical two-tier client/server architecture.
Clients

- Provide appropriate interfaces through a client software module to access and utilize the various server resources.
- Clients may be diskless machines or PCs or Workstations with disks with only the client software installed.
- Connected to the servers via some form of a network.
  - (LAN: local area network, wireless network, etc.)
DBMS Server

- Provides database query and transaction services to the clients.
- Relational DBMS servers are often called SQL servers, query servers, or transaction servers.
- Applications running on clients utilize an Application Program Interface (API) to access server databases via standard interface such as:
  - ODBC: Open Database Connectivity standard
  - JDBC: for Java programming access
Two Tier Client-Server Architecture

- Client and server must install appropriate client module and server module software for ODBC or JDBC
- A client program may connect to several DBMSs, sometimes called the data sources.
- In general, data sources can be files or other non-DBMS software that manages data.
- See Chapter 10 for details on Database Programming
Three Tier Client-Server Architecture

- Common for Web applications
- Intermediate Layer called **Application Server** or **Web Server**:
  - Stores the web connectivity software and the business logic (procedures or constraints) that are part of the application used to access the corresponding data from the database server
  - Acts like a conduit for sending partially processed data between the database server and the client.
- Three-tier Architecture Can Enhance Security:
  - Database server only accessible via middle tier
  - Clients cannot directly access database server
  - Clients contain user interfaces and Web browsers
  - The client is typically a PC or a mobile device connected to the Web
Three-tier client-server architecture

Figure 2.7
Logical three-tier client/server architecture, with a couple of commonly used nomenclatures.

Client → GUI, Web Interface

Application Server or Web Server

Database Server

Database Management System

Presentation Layer

Business Logic Layer

(a) (b)
Classification of DBMSs

- Based on the data model used
  - Currently Used: Relational, Object-oriented, Object-relational
  - Recent Technologies: Key-value storage systems, NOSQL systems: document based, column-based, graph-based and key-value based.
  - Native XML DBMSs.

- Other classifications
  - Single-user (typically used with personal computers) vs. multi-user (most DBMSs).
  - Centralized (uses a single computer with one database) vs. distributed (multiple computers, multiple DBs)
Variations of Distributed DBMSs (DDBMSs)

- Homogeneous DDBMS
- Heterogeneous DDBMS
- Federated (or Multidatabase) Systems
  - Participating Databases are loosely coupled with high degree of autonomy.
- Distributed Database Systems (DDBMS) have now come to be known as client-server based database systems because:
  - They do not support a totally distributed environment, but rather a set of database servers supporting a set of clients.
Cost considerations for DBMSs

- **Cost Range:** from free open-source systems to configurations costing millions of dollars
- Examples of free relational DBMSs: MySQL, PostgreSQL, others
- Commercial DBMS offer additional specialized modules, e.g. time-series module, spatial data module, document module, XML module
  - These offer additional specialized functionality when purchased separately
  - Sometimes called cartridges (e.g., in Oracle) or blades
- **Different licensing options:** site license, maximum number of concurrent users (seat license), single user, etc.
Other Considerations

- **Type of access paths within database system**
  - E.g.- inverted indexing based (ADABAS is one such system). Fully indexed databases provide access by any keyword (used in search engines)

- **General Purpose vs. Special Purpose**
  - E.g.- Airline Reservation systems or many others- reservation systems for hotel/car etc. Are special purpose OLTP (Online Transaction Processing Systems)
History of Data Models (Additional Material)

- Network Model
- Hierarchical Model
- Relational Model
- Object-oriented Data Models
- Object-Relational Models
History of Data Models

**Network Model:**

- The first network DBMS was implemented by Honeywell in 1964-65 (IDS System).
- Adopted heavily due to the support by CODASYL (Conference on Data Systems Languages) (CODASYL - DBTG report of 1971).
- Later implemented in a large variety of systems - IDMS (Cullinet - now Computer Associates), DMS 1100 (Unisys), IMAGE (H.P. (Hewlett-Packard)), VAX -DBMS (Digital Equipment Corp., next COMPAQ, now H.P.).
Network Model

Advantages:

- Network Model is able to model complex relationships (1:N) and represents semantics of add/delete on the relationships.
- Can handle most situations for modeling using record types and relationship types.
- Language is navigational; uses constructs like FIND, FIND member, FIND owner, FIND NEXT within set, GET, etc.
  - Programmers can do optimal navigation through the database.
Network Model

- Disadvantages:
  - Navigational and procedural nature of processing
  - Database contains a complex array of pointers that thread through a set of records.
    - Little scope for automated “query optimization”
History of Data Models

- **Hierarchical Data Model:**
  - Initially implemented in a joint effort by IBM and North American Rockwell around 1965. Resulted in the IMS family of systems.
  - IBM’s IMS product had (and still has) a very large customer base worldwide.
  - Hierarchical model was formalized based on the IMS system.
  - Other systems based on this model: System 2k (SAS inc.)
Hierarchical Model

- **Advantages:**
  - Simple to construct and operate
  - Corresponds to a number of natural hierarchically organized domains, e.g., organization ("org") chart
  - Language is simple:
    - Uses constructs like GET, GET UNIQUE, GET NEXT, GET NEXT WITHIN PARENT, etc.

- **Disadvantages:**
  - Navigational and procedural nature of processing
  - Database is visualized as a linear arrangement of records
  - Little scope for "query optimization"
History of Data Models

- **Relational Model:**
  - Proposed in 1970 by E.F. Codd (IBM), first commercial system in 1981-82.
  - Now in several commercial products (e.g. DB2, ORACLE, MS SQL Server, SYBASE, INFORMIX).
  - Several free open source implementations, e.g. MySQL, PostgreSQL
  - Currently most dominant for developing database applications.
  - SQL relational standards: SQL-89 (SQL1), SQL-92 (SQL2), SQL-99, SQL3, …
  - Chapters 5 through 11 describe this model in detail
History of Data Models

- **Object-oriented Data Models:**
  - Several models have been proposed for implementing in a database system.
  - One set comprises models of persistent O-O Programming Languages such as C++ (e.g., in OBJECTSTORE or VERSANT), and Smalltalk (e.g., in GEMSTONE).
  - Additionally, systems like O2, ORION (at MCC - then ITASCA), IRIS (at H.P.- used in Open OODB).
  - Chapter 12 describes this model.
History of Data Models

- **Object-Relational Models:**
  - The trend to mix object models with relational was started with Informix Universal Server.
  - Relational systems incorporated concepts from object databases leading to object-relational.
  - Exemplified in the versions of Oracle, DB2, and SQL Server and other DBMSs.
  - Current trend by Relational DBMS vendors is to extend relational DBMSs with capability to process XML, Text and other data types.
  - The term “Object-relational” is receding in the marketplace.
Chapter Summary

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- Schemas, Instances, and States
- Three-Schema Architecture
- Data Independence
- DBMS Languages and Interfaces
- Database System Utilities and Tools
- Database System Environment
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- History of Data Models