CMSC 724: Database Management Systems
Introduction/Background

Instructor: Amol Deshpande
amol@cs.umd.edu

Today

› Motivation: Why study databases ?

› Background: 424 Summary

› Administrivia
  ◦ Workload etc.

› No laptop use allowed in the class !!
Motivation: Data Explosion

- There is a *HUGE* amount of data in this world
- Everywhere you see...
- Personal
  - Emails, data on your computer
- Enterprise
  - The original primary motivation
  - Banks, supermarkets, universities, airlines, phone call data etc.
- Scientific
  - Biological, astronomical
- World wide web
  - Social networks etc...

Much more is produced every day

Wal-mart: 583 terabytes of sales and inventory data
  Adds a billion rows every day
  “we know how many 2.4 ounces of tubes of toothpastes sold yesterday and what was sold with them”

“Wellcome Trust Sanger Institute's World Trace Archive database of DNA sequences hit one billion entries..” [[ Since defunct ]]
  Stores all sequence data produced the world scientific community 22 Tbytes and doubling every 10 months

A single astrophysics simulation of galaxy formation can generate several PB of data, most of it thrown away
Motivation: Data Explosion

Machine-generated data
  
  Sensor devices/networks, microphones/camera, Web server logs, Network Monitoring, etc.

Online services (2 year old data)
  
  - Twitter: 177M tweets sent on 3/1/2011 (nothing special about the date), 572,000 accounts added on 3/12/2011
  - Dropbox: 1M files saved every 15 mins
  - Facebook: 135+ Billion Messages a Month
  - Reddit: 270 Million Page Views a Month in May 2010

Much of this data not stored in traditional RDBMS

Motivation: Data Explosion

<table>
<thead>
<tr>
<th>2 TERAYTE</th>
<th>3 PETABYTE</th>
<th>100 TERAYTE</th>
<th>300 TERAYTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 2TB HARD DRIVE THAT HOLDS 200,000 SONGS.</td>
<td>PHOTOS UPLOADED TO FACEBOOK EACH MONTH</td>
<td>ALL THE DATA AND IMAGES COLLECTED BY THE HUBBLE SPACE TELESCOPE.</td>
<td>DATA FROM THE LARGE HADRON COLIDER IS STORED EACH WEEK.</td>
</tr>
<tr>
<td>13 PB IN 2010</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1 TERAYTE</th>
<th>100 TERAYTE</th>
<th>1 PB TERYTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA PROCESSED BY GOOGLE SERVICES EVERY 10 MINUTES.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Motivation: Data Explosion

A major challenge to manage this data, answer queries over it, glean interesting and useful insights from it

“Big Data”
Everyone is either doing big data, or wants to...
No one seems to agree on what it really means 😞
Not just about scale/volume of data
Many of the datasets are not that large

“Data Scientist”
Goal: Extract meaning from data and creating data products
Need a broad range of skills: programming, statistics, math, ...
Data Management

A large fraction of the data still in traditional DBMS systems
Still open and active research areas about improving performance, energy efficiency, new functionalities, changing hardware spectrum (SSDs) and so on...

Much of the data not stored in traditional database systems
For a variety of fairly valid reasons
- Stream processing systems (focusing on streaming data)
- Special-purpose data warehousing systems (most start from some RDBMS)
- Batch analysis frameworks (like Hadoop, Pregel)
  Typically data stored in distributed file systems
- Key-value stores (like HBase, Cassandra, Redis, MongoDB, ...)
  Basically persistent distributed hash tables
- Semi-structured data stores (for XML query processing)
- Graph databases (somewhat new)
- Scientific data management (somewhat new)

However, many lessons to be learned from database research
We see much reinvention of the wheel and similar mistakes being made as early on
What we will cover

A large fraction of the data still in traditional DBMS systems
A deeper study of traditional RDBMS solutions (compared to 424)
New functionalities/features
Revisit some of the old design decisions (e.g., lay out data column-by-column instead of row-by-row, fully in-memory processing, etc)

Much of the data not stored in traditional database systems

Basic ideas behind, and why different from RDBMS:
- Stream processing systems
- Special-purpose data warehousing systems
- Batch analysis frameworks (specifically MapReduce)
- Key-value stores (focus on the consistency issues)

If time permits:
- Semi-structured data stores (we will cover XML model)
- Graph databases
- Scientific databases

Course Overview

- We will cover:
  - A blend of classic papers + ongoing research
  - Textbook:
  - Almost all papers are available online
  - Book contains some very nice overview chapters though
- Prerequisite: CMSC 424
  - Class notes off of my webpage
Course Overview: Grading

- 3 Programming Assignments (10%)
  - Small assignments, focusing on basics and some hands-on experience
  - Will post them today or tomorrow
- Paper readings + Class Participation (15%)
  - Unlike previous years, no critique requirement
  - Instead you must answer some very simple questions about the readings (for each week’s reading)
  - I will keep track of participation in the class/Piazza forum
- Instead: 6 Written Assignments (30%)
- Research project + Presentation (30%)
  - More on that in the next class
  - Presentations in the second half on the “problem definition+background”
- Final (15%)
  - Basically a slightly longer written assignment

Current Industry Outlook

- Relational DBMSs
  - Oracle, IBM DB2, Microsoft SQL Server, Sybase

- Open source alternatives
  - MySQL, PostgreSQL, Apache Derby, BerkeleyDB (mainly a storage engine – no SQL), neo4j (graph data) ...

- Data Warehousing Solutions
  - Geared towards very large volumes of data and on analyzing them
  - Long list: Teradata, Oracle Exadata, Netezza (based on FPGAs), Aster Data (founded 2005), Vertica (column-based), Kickfire, Xtremedata (released 2009), Sybase IQ, Greenplum (eBay, Fox Networks use them)
  - Usually sell package/services and charge per TB of managed data
  - Many (especially recent ones) start with MySQL or PostgreSQL and make them parallel/faster etc..
Web Scale Data Management, Analysis

- Ongoing debate/issue
  - Cloud computing seems to eschew DBMSs in favor of homegrown solutions
  - E.g. Google, Facebook, Amazon etc...

- MapReduce: A paradigm for large-scale data analysis
  - Hadoop: An open source implementation

Why?
- DBMSs can’t scale to the needs, not fault-tolerant enough
  - These apps don’t need things like transactions, that complicate DBMSs (???)
  - Mapreduce favors Unix-style programming, doesn’t require SQL
  - Try writing SVMs or decision trees in SQL
- Cost
  - Companies like Teradata may charge $100,000 per TB of data managed

Current Industry Outlook

- Bigtable-like
  - Called “key-value stores”
  - Think highly distributed hash tables
  - Allow some transactional capabilities – still evolving area
  - PNUTS (Yahoo), Cassandra (Facebook), Dynamo (Amazon)

- Mapreduce-like
  - Hadoop (open source), Pig (@Yahoo), Dryad (@Microsoft)
  - Amazon EC2 Framework
  - Not really a database – but increasing declarative SQL-like capabilities are being added (e.g. HIVE at Facebook)
My Current Research Interests

- Managing and querying large graph-structured datasets
- Data management for cloud
  - Programming frameworks; transaction management
- Scalable analytics and statistical modeling
- Managing and reasoning about uncertainty in data

- Suggestions for class projects will skew in those directions

- Older work:
  - Data streams, Adaptive query processing, Sensor network data management

Databases: Major Conferences

- ACM SIGMOD (Originally SIGFIDET)
- VLDB (very large databases)
- IEEE ICDE (int'l. conf. data engineering)
- EDBT (European database technology)
- PODS, ICDT
  - Theory focused
- CIDR
  - A new systems focused conference, perhaps the best one right now to attend
  - I recommend browsing through 2015 proceedings for ideas on class projects
Today

- Motivation: Why study databases?
- Background: 424 Summary

- No laptop use allowed in the class!!

Why not use file systems?

- Drawbacks of using file systems to store data:
  - Data redundancy and inconsistency
    - Multiple file formats, duplication of information in different files
  - Difficulty in accessing data
    - Need to write a new program to carry out each new task
  - Data isolation — multiple files and formats
  - Integrity problems
    - Integrity constraints (e.g., account balance > 0) become “buried” in program code rather than being stated explicitly
    - Hard to add new constraints or change existing ones
Why not use file systems?

Drawbacks of using file systems to store data:

- Atomicity of updates
  - Failures may leave database in an inconsistent state with partial updates carried out
  - Example: Transfer of funds from one account to another should either complete or not happen at all
- Concurrent access by multiple users
  - Concurrent access needed for performance
  - Uncontrolled concurrent accesses can lead to inconsistencies
    - Example: Two people reading a balance (say 100) and updating it by withdrawing money (say 50 each) at the same time
- Security problems
  - Hard to provide user access to some, but not all, data

DBMSs to the Rescue

- Provide a systematic way to answer many of these questions...
- Aim is to allow easy management of high volumes of data
  - Storing, Updating, Querying, Analyzing ....

What is a Database?

- A large, integrated collection of (mostly structured) data
- Typically models and captures information about a real-world enterprise
  - Entities (e.g. courses, students)
  - Relationships (e.g. John is taking CMSC 424)
- Usually also contains:
  - Knowledge of constraints on the data (e.g. course capacities)
  - Business logic (e.g. pre-requisite rules)
  - Encoded as part of the data model (preferable) or through external programs
DBMSs to the Rescue

- Massively successful for *highly structured data*
  - Why? Structure in the data (if any) can be exploited for ease of use and efficiency
    - If there is no structure in the data, hard to do much
    - Contrast managing emails vs managing photos
  - Much of the data we need to deal with is highly structured
    - Some data is *semi-structured*
      - E.g.: Resumes, Webpages, Blogs etc.
    - Some has complicated structure
      - E.g.: Social networks
    - Some has no structure
      - E.g.: Text data, Video/Image data etc.

Structured vs Unstructured Data

- A lot of the data we encounter is structured
  - Some have very simple structures
    - E.g. Data that can be represented in tabular forms (i.e., as relations)
  - Significantly easier to deal with

<table>
<thead>
<tr>
<th>Account</th>
<th>Customer</th>
</tr>
</thead>
<tbody>
<tr>
<td>bname</td>
<td>cname</td>
</tr>
<tr>
<td>acct_no</td>
<td>cstreet</td>
</tr>
<tr>
<td>balance</td>
<td>ccity</td>
</tr>
<tr>
<td>Downtown Mianus Perry R.H</td>
<td>Jones Smith Hayes Curry Lindsay</td>
</tr>
<tr>
<td>A-101</td>
<td>Main</td>
</tr>
<tr>
<td>A-215</td>
<td>North</td>
</tr>
<tr>
<td>A-102</td>
<td>Main</td>
</tr>
<tr>
<td>A-305</td>
<td>North</td>
</tr>
<tr>
<td>500</td>
<td>Harrison</td>
</tr>
<tr>
<td>700</td>
<td>Rye</td>
</tr>
<tr>
<td>400</td>
<td>Harrison</td>
</tr>
<tr>
<td>350</td>
<td>Rye</td>
</tr>
<tr>
<td>500</td>
<td>Pittsfield</td>
</tr>
</tbody>
</table>
Structured vs Unstructured Data

- Some data has a little more complicated structure
  - E.g. graph structures
    - Map data, social networks data, the web link structure etc
  - Can convert to tabular forms for storage, but may not be optimal
  - Queries often reason about graph structure
    - Find my “Erdos number”
    - Suggest friends based on current friends
  - Growing importance in recent years in a variety of domains: Biological, social networks, web...

- A major research focus for me and others here

Structured vs Unstructured Data

- Increasing amount of data in a semi-structured format
  - XML – Self-describing tags (HTML ?)
  - Complicates a lot of things
  - We will discuss this toward the end

- A huge amount of data is unfortunately unstructured
  - Books, WWW
  - Amenable to pretty much only text search... so far
    - Information Retrieval research deals with this topic
  - What about Google search?
    - Google search is mainly successful because it uses the structure (in its original incarnation)

- Video? Music?
  - Can represent in DBMS’s, but can’t really operate on them
DBMSs to the Rescue

- Massively successful for *highly structured data*
  - Why? Structure in the data (if any) can be exploited for ease of use and efficiency
  - How?
    - Two Key Concepts:
      - **Data Modeling**: Allows reasoning about the data at a high level
        - e.g. “emails” have “sender”, “receiver”, “…"
        - Once we can describe the data, we can start “querying” it
      - **Data Abstraction/Independence**: Layer the system so that the users/applications are insulated from the low-level details

DBMSs to the Rescue: Data Modeling

- Data modeling
  - **Data model**: A collection of concepts that describes how data is represented and accessed
  - **Schema**: A description of a specific collection of data, using a given data model
  - Some examples of data models that we will see
    - Relational, Entity-relationship model, XML...
    - Object-oriented, object-relational, semantic data model, RDF...
  - Why so many models?
    - Tension between descriptive power and ease of use/efficiency
    - More powerful models \(ightarrow\) more data can be represented
    - More powerful models \(\rightarrow\) harder to use, to query, and less efficient
DBMSs to the Rescue: Data Abstraction

- Also called “Data Independence”

- Probably the most important purpose of a DBMS
- Goal: Hiding low-level details from the users of the system
  - Alternatively: the principle that
    - applications and users should be insulated from how data is structured and stored

- Through use of logical abstractions

Data Abstraction

What data users and application programs see?

What data is stored?
- describe data properties such as data semantics, data relationships

How data is actually stored?
- e.g. are we using disks? Which file system?

View Level
- View 1
- View 2
- ...
- View n

Logical Level

Physical Level
Data Abstraction

Logical Data Independence
Protection from logical changes to the schema

Physical Data Independence
Protection from changes to the physical structure of the data

Logical Level

Physical Level

Data Abstractions: Example

A View Schema
course_info(#registered, …)

Logical Schema
students(sid, name, major, …)
courses(cid, name, …)
enrolled(sid, cid, …)

Physical Schema
all students in one file ordered by sid
courses split into multiple files by colleges
What about a Database System?

- A DBMS is a software system designed to store, manage, facilitate access to databases

- Provides:
  - Data Definition Language (DDL)
    - For defining and modifying the schemas
  - Data Manipulation Language (DML)
    - For retrieving, modifying, analyzing the data itself

- Guarantees about correctness in presence of failures and concurrency, data semantics etc.

Common use patterns

- Handling transactions (e.g. ATM Transactions, flight reservations)
- Archival (storing historical data)
- Analytics (e.g. identifying trends, Data Mining)

Relational DBMS: SQL

- SQL (sequel): Structured Query Language

- Data definition (DDL)
  - `create table instructor (` 
    - `ID` char(5),
    - `name` varchar(20),
    - `dept_name` varchar(20),
    - `salary` numeric(8,2))`

- Data manipulation (DML)
  - Example: Find the name of the instructor with ID 22222
    - `select name` 
      - `from instructor` 
      - `where instructor.ID = ‘22222’`
Basic topics covered in 424

- representing information
  - data modeling
  - semantic constraints
- languages and systems for querying data
  - complex queries & query semantics
  - over massive data sets
- concurrency control for data manipulation
  - ensuring transactional semantics
- reliable data storage
  - maintain data semantics even if you pull the plug
  - fault tolerance

Basic topics covered in 424

- representing information
  - data modeling: relational models, E/R models
  - semantic constraints: integrity constraints, triggers
- languages and systems for querying data
  - complex queries & query semantics: SQL
  - over massive data sets: indexes, query processing, optimization
- concurrency control for data manipulation
  - ensuring transactional semantics: ACID properties
- reliable data storage
  - maintain data semantics even if you pull the plug: durability
  - fault tolerance: RAID
Relational Data Model

- Most widely used model today
- Main concepts:
  - relation: basically a table with rows and columns
  - schema (of the relation): description of the columns
- Example:
  - courses(dept char(4), courseID integer, name varchar(80), instructor varchar(80))
  - students(sid char(9), name varchar(80), ...)
  - enrolled(sid char(9), courseID integer, ...)
- This is pretty much the only construct

<table>
<thead>
<tr>
<th>Dept</th>
<th>CourseID</th>
<th>Name</th>
<th>Instructor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMSC</td>
<td>424</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMSC</td>
<td>427</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An instance of the courses relation

Entity-Relationship (E/R) Data Model

- More powerful model, commonly used during conceptual design
  - Easier and more intuitive for users to work with in the beginning
- Has two main constructs:
  - Entities: e.g. courses, students
  - Relationships: e.g. enrolled
- Diagrammatic representation
Relational Query Languages

- Example schema: \( R(A, B) \)
- Practical languages
  - SQL
    - select A from R where B = 5;
  - Datalog (sort of practical) – Has seen a resurgence in recent years
    - \( q(A) :- R(A, 5) \)
- Formal languages
  - Relational algebra
    - \( \pi_A ( \sigma_{B=5} (R) ) \) -- You will encounter this in many papers
  - Tuple relational calculus
    - \{ t : \{A\} | \exists s : \{A, B\} ( R(A, B) \land s.B = 5 ) \}
  - Domain relational calculus
    - Similar to tuple relational calculus

Relational Query Languages

- Important thing to keep in mind:
  - SQL is not SET semantics, it is BAG semantics
  - i.e., duplicates are not eliminated by default
    - With the exception of UNION, INTERSECTION, MINUS
  - Relational model is SET semantics
    - Duplicates cannot exist by definition
- Relational algebra: Six basic operators
  - Select (\( \sigma \)), Project (\( \Pi \)), Cartesian Product (\( \times \))
  - Set union (\( U \)), Set difference (\( - \))
  - Rename (\( \rho \))
Join Variations (SQL and Relational Alg.)

- Tables: \( r(A, B) \), \( s(B, C) \)

<table>
<thead>
<tr>
<th>name</th>
<th>Symbol</th>
<th>SQL Equivalent</th>
<th>RA expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>cross product</td>
<td>( \times )</td>
<td>select * from ( r ), ( s );</td>
<td>( r \times s )</td>
</tr>
<tr>
<td>natural join</td>
<td>( \bowtie )</td>
<td>natural join</td>
<td>( \pi_{A,B,C} \sigma_{B=\text{constant}}(r \times s) )</td>
</tr>
<tr>
<td>theta join</td>
<td>( \bowtie_\theta )</td>
<td>from .. where ( \theta );</td>
<td>( \sigma_\theta(r \times s) )</td>
</tr>
<tr>
<td>equi-join</td>
<td>( \bowtie_\theta )</td>
<td>(theta must be equality)</td>
<td></td>
</tr>
<tr>
<td>left outer join</td>
<td>( r \bowtie \ s )</td>
<td>left outer join (with “on”)</td>
<td>(see previous slide)</td>
</tr>
<tr>
<td>full outer join</td>
<td>( r \bowtie \ s )</td>
<td>full outer join (with “on”)</td>
<td>-</td>
</tr>
<tr>
<td>(left) semijoin</td>
<td>( r \bowtie \ s )</td>
<td>none</td>
<td>( \pi_{A,B}(r \bowtie \ s) )</td>
</tr>
<tr>
<td>(left) antijoin</td>
<td>( r \bowtie \ s )</td>
<td>none</td>
<td>( r \setminus \pi_{A,B}(r \bowtie \ s) )</td>
</tr>
</tbody>
</table>

Relational Model: Normalization

- Goal: What is a “good” schema for a database? How to define and achieve that

- Problems to avoid:
  - Repetition of information
    - For example, a table:
      - \( \text{accounts(owner(SSN), account_no, owner_name, owner_address, balance)} \)
    - Inherently repeats information if a customer is allowed to have more than one account
  - Avoid set-valued attributes
Relational Model: Normalization

1. Encode and list all our knowledge about the schema
   - Functional dependencies (FDs)
     - SSN → name (means: SSN “implies” name)
     - If two tuples have the same “SSN”, they must have the same “name”
       - movietitle → length ??? Not true.
     - But, (movietitle, movieYear) → length --- True.

2. Define a set of rules that the schema must follow to be considered good
   - “Normal forms”: 1NF, 2NF, 3NF, BCNF, 4NF, ...
   - A normal form specifies constraints on the schemas and FDs

3. If not in a “normal form”, we modify the schema

See 424 class notes for more

Semantic Constraints

- SQL supports defining integrity constraints over the data
  - Basically a property that must always be valid
  - E.g., a customer must have an SSN, a customer with a loan must have a sufficiently high balance in checking account, etc.

- Triggers
  - If something happens, then execute something
    - E.g., if a tuple inserted in table R, then update table S as well
    - Quite frequently used in practice, and surprising not as well optimized for large numbers
Storage

- Storage:
  - Need to be cognizant of the memory hierarchy
    - Many of traditional DBMS decisions are based on:
      - Disks are cheap, memory is expensive
      - Disks much faster to access sequentially than randomly
      - Much work in recent years on revisiting the design decisions...
  - RAID: Surviving failures through redundancy

Indexes

- One of the biggest keys to efficiency, and heavily used
- **B+-trees** most popular and pretty much the only ones used in most systems
- Others: R-trees, kD-trees, ...

Query Processing

1. Parsing and translation
2. Optimization
3. Evaluation
Transactions

- **Transaction**: A sequence of database actions enclosed within special tags
- **Properties**:
  - **Atomicity**: Entire transaction or nothing
  - **Consistency**: Transaction, executed completely, takes database from one consistent state to another
  - **Isolation**: Concurrent transactions *appear* to run in isolation
  - **Durability**: Effects of committed transactions are not lost
- Consistency: programmer needs to guarantee that
  - DBMS can do a few things, e.g., enforce constraints on the data
- Rest: DBMS guarantees

Transactions: How?

- **Atomicity**: Through “logging” of all operations to “stable storage”, and reversing if the transaction did not finish
- **Isolation**:
  - Locking-based mechanisms
  - Multi-version concurrency control
- **Durability**: Through “logging” of all operations to “stable storage”, and repeating if needed
- Some key concepts:
  - Two-phase locking, Write-ahead logging
Next week..

- History of databases + Data modeling
  - Reading: The first chapter in the book
  - Reading: Ted Codd's paper
  - Reading: XML
- After that: Architecture of a database system