Where do data come from?
CS100 - Guest Lecture - Databases and Provenance

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Outline

1. Who I am
2. What are Databases?
3. Data Provenance
4. Questions
Hi, I am Boris
Hi, I am Boris

I am a **database** guy!
Hi, I am Boris

I am a database guy!

I will tell you:
1) Why DBs are important
2) Why DBs are interesting
3) My Research
1. Who I am
2. What are Databases?
3. Data Provenance
4. Questions
Where do data come from?
You might have heard . . .
Database systems and databases

- database systems manage databases
- a database is a structured collection of data

What do database systems do?

1. Provide **persistent** storage of data
2. Efficient **declarative** access to data: querying
3. Protection from data loss under failures
4. Safe concurrent access to data
Most large software systems use databases!
- Business Intelligence, e.g., IBM cognos
- Web-based systems

Desktop software
- You music player
- You email client (most likely at least)

Every big company uses DBs
- banks
- insurance
- government agencies
- ...
Who Creates Databases?

- **Relational databases is big business**
  - IBM DB2
  - Oracle
  - Microsoft SQLServer
  - Teradata
  - Open Source Systems: PostgreSQL, MySQL

- **Distributed systems**
  - Cloud storage and Key-value stores
    - Amazon S3, Google Big Table, Cassandra
  - Big Data Analytics
    - MapReduce, Spark, Flink
Why Are Database Interesting?

Combination of systems and theoretical research

- **Interesting systems problems**
  - Hacking complex and large systems
  - Low-level optimizations
    - exploit modern hardware

- **Interesting theoretical foundations**
  - Complexity of answering queries
  - Expressiveness of query languages
  - Strong connections to logic
Connections to other CS fields

- Distributed systems
  - getting more and more important
- Compilers
- Modeling
- AI and machine learning
  - Data mining
- Operating and File Systems
The Relational Datamodel

Relations aka Tables

- a table consists of **columns** and **rows**
- tables store one type of entity
  - *e.g.*, students, bank accounts, loans, ...
- each row is one entity
  - *e.g.*, one student
- columns store a particular type of information about an entity
  - *e.g.*, name of a student
### Example Tables

#### Students table

<table>
<thead>
<tr>
<th>CWID</th>
<th>Name</th>
<th>Major</th>
<th>GPA</th>
<th>Phone</th>
</tr>
</thead>
<tbody>
<tr>
<td>A13333331</td>
<td>Peter</td>
<td>CS</td>
<td>3.5</td>
<td>312 555 8888</td>
</tr>
<tr>
<td>A5552341</td>
<td>Alice'</td>
<td>CS</td>
<td>4.0</td>
<td>312 555 7777</td>
</tr>
<tr>
<td>A1325324</td>
<td>Elisa</td>
<td>Bio</td>
<td>3.2</td>
<td>312 555 5555</td>
</tr>
</tbody>
</table>

#### Grades table

<table>
<thead>
<tr>
<th>CWID</th>
<th>Course</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>A13333331</td>
<td>CS100</td>
<td>A</td>
</tr>
<tr>
<td>A5552341</td>
<td>CS425</td>
<td>C</td>
</tr>
<tr>
<td>A1325324</td>
<td>CS525</td>
<td>A</td>
</tr>
<tr>
<td>A1325324</td>
<td>CS566</td>
<td>B</td>
</tr>
</tbody>
</table>
What do I do with the data in my database?

- you can interrogate the database system to extract information about your data
- this is done using a programming language called SQL
- SQL is a **declarative** language
  - say what data you want not how to compute it
- Queries return table (closed language)
 Queries (cont.)

<table>
<thead>
<tr>
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</tr>
</tbody>
</table>

- **How many students are in my database?**
  \[ \text{#Students} = 3 \]

- **Who has the highest GPA?**
  Name: Alice

- **What are the names of CS students?**
  Name: Peter, Alice
Persistence and Recovery

What if you shutdown your computer?
- will you lose your precious data?

What happens when your computer crashes?
- will you lose your precious data?
### Persistence and Recovery

<table>
<thead>
<tr>
<th>What if you shutdown your computer?</th>
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</thead>
<tbody>
<tr>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No!</th>
</tr>
</thead>
<tbody>
<tr>
<td>- the database system stores your data on stable storage (disk)</td>
</tr>
<tr>
<td>- database systems know how recover from failures</td>
</tr>
<tr>
<td>- when the database system signals to you that a change you made was applied then you will never loose it</td>
</tr>
</tbody>
</table>
**Concurrent Access**

**Banking Example**
- **Account A**: $50
- **Account B**: $50
- Transfer $25 from A to B
- Bank gives all accounts 10% interest

**Transfer Money**
- **Action**
  - Subtract $25 from A
  - Add $25 to B

**Give 10% interest**
- **Action**
  - Add 5% interest

**Balances**

<table>
<thead>
<tr>
<th>Account A</th>
<th>Account B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$25</td>
<td>$50</td>
</tr>
<tr>
<td>$27.5</td>
<td>$55</td>
</tr>
<tr>
<td>$27.5</td>
<td>$80</td>
</tr>
</tbody>
</table>

**We have lost interest!**
Concurrent Access (cont.)

Concurrency Control
- databases manage concurrent operations
- prevent bad things from happening
- from user perspective:
  - behaves like your program is the only one running!

Can we lose interest?
Nope!
Outline

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What is Provenance?

Provenance in Art

- record of ownership of a piece of art

Arnolfini Portrait

The provenance of the painting begins in 1434 when it was dated by van Eyck and presumably owned by the sitter(s). At some point before 1516 it came into the possession of Don Diego de Guevara (d. Brussels 1520), a Spanish career courtier of the Habsburgs . . . By 1516 he had given the portrait to Margaret of Austria, . . .
What is Provenance?

Provenance in Databases
- Records how data was produced
  - which other data was used in the creation process
  - which operations were involved in its creation
- For sake of this lecture, only provenance of queries

Provenance of a query result
- Select one row from the result of a query
- Which input rows were used to compute it?
- Maybe also: how were these rows combined
Compute average salary of employees per department

```
SELECT dept, avg(salary) AS avgsal
FROM emp
GROUP BY dept
```

<table>
<thead>
<tr>
<th>name</th>
<th>salary</th>
<th>dept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peter</td>
<td>10</td>
<td>HR</td>
</tr>
<tr>
<td>Bob</td>
<td>20</td>
<td>HR</td>
</tr>
<tr>
<td>Alice</td>
<td>5</td>
<td>IT</td>
</tr>
</tbody>
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Compute average salary of employees per department

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</table>

```
SELECT dept, avg(salary) AS avgsal
FROM emp
GROUP BY dept
```
The first result row depends on the first two input rows

<table>
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<th>dept</th>
<th>avgsal</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR</td>
<td>15</td>
</tr>
<tr>
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Provenance maps output rows of queries to input rows

- here track this per row
- could also track attribute values (higher fidelity)
- could also track tables (lower fidelity)
### Why should I care?

- Debugging queries and data
- Auditing
- Explainability
- Optimizing DB operations
- Determining trust in data

**Use cases**
Functional View of Querying

- A query takes as input a database and outputs a table.
- We can think about queries as functions from databases to result tables!

What then is provenance?

- Select one of the outputs of the query.
- Which inputs were used to compute it?
What are functions in math?

- You already know functions from high school math!
Recap Functions

What are functions in math?

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Examples

- \( f(x) = x \)
  - \( f(1) = 1 \)
What are functions in math?

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Examples

- $f(x) = x$
  - $f(1) = 1$
  - $f(2) = 2$
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Recap Functions
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- $f(x, y) = x + y$
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  - \( f(2) = 4 \)
  - \( \ldots \)

- \( f(x, y) = x + y \)
  - \( f(1, 2) = 1 + 2 = 3 \)
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- \( f(x, y) = x + y \)
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  - \( \ldots \)
Recap Functions (cont.)

What makes a function a function?

- Does it have to return numbers?
- Does it have to take numbers as input?

Counterexamples

- $f$ takes names as an input and returns the name converted to lower case
  - $f(Peter) = peter$
  - $f(Bob) = bob$
- $f$ takes text as input and returns the numbers of characters in the text
  - $f(Bob) = 3$
  - $f(Alice) = 5$
### Definition (Function)

- **Input domain**: A set of values $\mathcal{I}$
- **Output domain**: A set of value $\mathcal{O}$
- **Mapping**: Associate each value from $\mathcal{I}$ with **one** value from $\mathcal{O}$

### Queries as Functions

- **Input domain**: databases
- **Output domains**: tables
What is the Provenance of a Function?

Provenance = Inversion?

- We want to understand which input was used to generate an output
- In math this is called function inversion
- The inverse $f^{-1}$ of a function $f$ takes an output of $f$ and returns the corresponding input
  - When $f(x) = y$ then $f^{-1}(y) = x$

Examples

- If $f(x) = 2x$, then $f^{-1}(x) = \frac{x}{2}$
- If $f(x) = x^3$, then $f^{-1}(x) = \sqrt[3]{x}$
- If $f(x) = x^2$, then $f^{-1}(x) = \sqrt{x}$
  - This does not work (two possible solutions)
What is the Provenance of a Function?

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Examples

- If $f(x) = 2x$ then $f^{-1}(x) = 0.5x$.
- If $f(x) = x^3$ then $f^{-1}(x) = \sqrt[3]{x}$. This does not work (two possible solutions).
What is the Provenance of a Function?

Provenance = Inversion?

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- If $f(x) = x^2$ then $f^{-1}(x) = \sqrt{x}$? (this does not work, two possible solutions.)
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What is the Provenance of a Function?

**Provenance = Inversion?**

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**Examples**

- if $f(x) = 2x$ then $f^{-1}(x) = 0.5x$
- if $f(x) = x^3$ then $f^{-1}(x) = \sqrt[3]{x}$
- if $f(x) = x^2$ then $f^{-1}(x) = \sqrt{x}$?
  - this does not work (two possible solutions)
### Queries are typically not invertible!

- Return the number of students in CS100
- Let’s say the result is 3 students
- Inverse function would have to magically guess who these 3 students are!

### Queries operate on tables

- We want more fine-granular information:
  - Which rows from the input affected which rows from the output!
### Quadratic function

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>4</td>
</tr>
<tr>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

- Cannot invert this
- The output is not enough to compute provenance!
- How can we deal with that?
“Magic Machine”
“Magic Machine”
Generalizing the solution

Approach
- annotate input data with unique identifiers (colors)
- outputs annotated with the color of the input they are derived from

Quadratic function

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-2, ■)</td>
<td>(4, ■)</td>
</tr>
<tr>
<td>(-1, □)</td>
<td>(1, □)</td>
</tr>
<tr>
<td>(0, △)</td>
<td>(0, △)</td>
</tr>
<tr>
<td>(1, ▽)</td>
<td>(1, ▽)</td>
</tr>
<tr>
<td>(2, ◆)</td>
<td>(4, ◆)</td>
</tr>
</tbody>
</table>
Caveats

- We assumed that the function happily accepts inputs that are pairs of numbers and colors.
- If inputs and outputs are tables then we need to understand the internals of the function to know how they are related.
Provenance for Queries (how it is actually done)

Encode annotations by extending tables
- each row is extended with extra attributes
- these attributes are used to store provenance

Query instrumentation
- We rewrite queries input queries into queries that
  1. create annotations for each input
  2. propagate these annotations to produced annotated outputs
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DBGroup - What do we do?

**Distributed and High-performance Databases**
- HRDBMS - a scalable database with high per-node performance
- HCDF - operating system - database co-design

**Data Integration and Cleaning**
- how to systematically evaluate cleaning and integration systems
  - Bart
  - iBench

**Data Provenance**
- GProM - a generic provenance middleware
- Relevance-based Data Management - optimizing data operations based on what data is relevant
Data Science

- We are data science enablers!
- Vizier - a data-centric notebook platform with uncertainty tracking
Questions?

- IIT DBGroup
  - students: 7 Ph.D., 1 Master, 1 Undergraduate
  - research group: http://www.cs.iit.edu/~dbgroup/
  - personal page:
  - github: https://github.com/IITDBGroup