what is a database?
- collection of structured data
  - typically organized as "records" (traditionally, large #, on disk)
  - and relationships between records

this class is about database management systems
(system for creating, manipulating, accessing a database)

Why should you care?
- There are lots of applications that we don't offer classes on at MIT.

Why are databases any different?
- Ubiquity + real world impact + software market (roughly same size as OS market)
  (most web sites, most big companies)
manage both day to day ops as well as business intelligence + data mining
Core 6.830 Concepts

- Data modeling
- Declarative Query Language, Query Processing, Efficient Data Access
- Consistency / Transactions (“ACID”)

Today:

Why database systems?

User’s perspective:
- Modeling data
- Querying data

Zoo admin interface
- edit
- add animal

public
- pictures + maps

zookeeper
- feeding

1K animals, 5K pages, 10 admins, 200 keepers

- Fundamental concepts:
  - **Data models**
    - Systematic approach to structuring / representing data
    - Important for consistency, sharing, efficiency of access to persistent data
  - **Declarative Querying and Query Processing**
    - High level language for accessing data
    - Say what I want, not how to do it
    - "Data Independence"
    - Compiler that finds optimal plan for data access
    - Many low-level techniques for efficiently getting at data

- **Consistency / Transactions + Concurrency Control**
  - **Atomicity** -- Complex operations can be thought of as a single atomic operation that either completes or fails; partial state is never exposed
  - **Consistency and Isolation** -- Semantics of concurrent operations are well defined -- equivalent to a serial execution, respecting invariants over time
  - **Durability** -- Completed operations persist after a failure

- **Distributed data processing**

  Makes programming applications MUCH easier, since you don’t have to reason about arbitrary interleavings of concurrent code, and you know that the database will always be in a consistent state

  - A bit of many fields: systems, algorithms and data structures, languages + language design, more recently AI + learning, distributed systems….

- This course will look in detail at these areas, as well as a number of papers current in DBMS research, e.g., streaming, large scale data processing.

ZooFS: store each page in a text file

**ZooFS Ops:**
- move each snake to a new bldg
- custom code, consistency issues
- multiple simultaneous admins "concurrency control"
- system crashes
- pages in uncertain state
- hungriest animal
- custom code, slow

Importance of these concepts far exceeds the specific artifact that most of us would call a database (SQL, transactions, etc) — we will learn about those artifacts and also the “big ideas” (mapd demo)

**suppose i am creating a web site that stores information about a zoo.**

- admin interface that allows me to add new animals, edit animals
- public interface that allows me to look at pictures and maps
- zookeeper interface to find the animals that need to be fed

**why not just use a file system? what does a database give the developer?**
Modeling
Features to capture
How to (logically) represent data

Features:
Animals: name, age, species, cage
Cages: feedtime, bldgs

Data Model: logical structures used for data
Tabular:

<table>
<thead>
<tr>
<th>name</th>
<th>age</th>
<th>species</th>
<th>cageno</th>
</tr>
</thead>
<tbody>
<tr>
<td>peter</td>
<td>13</td>
<td>giraffe</td>
<td>1</td>
</tr>
<tr>
<td>sam</td>
<td>3</td>
<td>salam</td>
<td>2</td>
</tr>
<tr>
<td>sally</td>
<td>1</td>
<td>student</td>
<td>1</td>
</tr>
</tbody>
</table>

Data Model: logical structures used for data

<table>
<thead>
<tr>
<th>no</th>
<th>feedtime</th>
<th>bldg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1:30</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2:30</td>
<td>2</td>
</tr>
</tbody>
</table>

Operations
- suppose move all the snakes to a new building
  - database => queries

- suppose multiple admins try to edit the same page at the same time
  - need some kind of locking
  - database => ("concurrency control")

- suppose the system crashes mid-update
  - pages might be in uncertain states
  - database provides
    - transactions + recovery
    - groups of actions that happen atomically -- "all or nothing"

- suppose i want to find the animal that was fed the longest ago
  - have to write a complex program
  - could be very slow if it has to read and search all of the pages

long history of file system research that tries to fix these issues

Databases address all of these issues.

Let's look at how data might be structured in database

What features of our zoo do we want to capture? ("Entity Relationship Diagram" — see slide)
  - each animal has a name, age, species, and is in a cage
  - each cage gets fed at a particular time, is in a particular building
  - each cage is kept by many keepers
  - each keeper keeps many cages
  - each animal is in one cage, each cage has many animals

"data model" --> "schema"

Relational data model -- tables that represent entities and their properties

(Show slide)

Translations into tables by taking all of the one-to-one relations and putting them in table named for object.

Many to many relationships require an intermediate mapping table

what else? hierarchy (json) network triplets

Logical vs physical
6.830: Relational Model

Many possible representations of a given data set

<table>
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</table>

“Normalization”

User’s perspective: Querying
“names of giraffes”

for each row r in animals
if r.type = giraffes
output r.name

“selection query”
SELECT r.name FROM animals
WHERE r.type = giraffes

E.g., can represent a hierarchy via an XML file. Can represent a graph as a C struct with pointers to related nodes. Can represent a table as row-wise files of bytes, or as a linked list, or as a tree.

What is the advantage a logical/physical separation? Disadvantages?

Suppose we are using tables? Which logical representation is best? Why? Which physical representation is best?

Mostly, in this class, we will talk about the tabular -- relational -- approach.

why is it called relational?
because each record is a relation between fields (“keys” capture relations)

note that there are many possible relations for a given set of data
(example with joined column)

rules for choosing the best set of relations for a given data set
“schema normalization”

For now, we’ll use a physical representation similar to the logical representation -- e.g., rows in a file.

what kind of operations might I want to perform on a relation? (see slides)

find the names of animals that are giraffes. (1)

find the animals in a cage in bldg 32. (you guys) -- “join” (2)

find the average age of the bears. (3)

insert an a new snake named bill INSERT
delete barney DELETE
move the snakes to a new cage UPDATE

This logical representation is different from the physical representation -- e.g., the layout in memory or on disk -- is different than the logical representation the programs and users see.
Under the covers -- Declarative queries:

- multiple procedural plans
- sorted animals on type => binary search
  - search performance
  - update performance

Indices: map from (value) -> (record list)

Declarative query -> unoptimized procedural plan ->
optimized plan -> compiled program

select (bldg = 2) (binary search?)
    |
    join (r1.cage = r1.no)
    /     \
  /        \       \
/          |        |
animals   cages
r1         r2

Declarative:
Notice, however, that our procedural programs are not the only way to compute the answers to these queries!

When could I do something besides the procedural programs shown above:

For example, if we store animals in animal type order, we can use binary search to find the animals of a particular type quickly.

Is there a cost to doing this?

Have to store in sorted order (more expensive inserts)

Lots of other possibilities -- e.g., can have hash table (index) that maps from type -> records

Declarative query -> unoptimized plan -> optimized plan -> physical plan

Query optimization -- Depending on physical representation of data, and type of query, DBMS selects what it believes to be the best plan. Uses a cost model to estimate how long different plans will take to run.

Optimization selects which implementation of each operation to use, as well as order of individual operations -- e.g., can move selection below join.

In declarative programming, the physical representation -- e.g., the layout in memory or on disk -- is different than the logical representation the user’s programs interact with. Optimizer’s job is to implement the logical query effectively on physical representation.

In standard imperative programming, logical and physical representation are typically more closely aligned.

E.g. can store the table in sorted order, or not. Repr is not exposed in SQL, or app!

Decoupling of logical model from physical representation is known as “data independence”

Can store the data in different ways on disk, don’t have to change program

PS1 -- learn SQL; due 1 week from next Tuesday, will release early next week