Databases

Storing Data

Format	Where
Fixed field record	Used in punch cards, each record can store 80 characters, some of the 80 characters are allocated to different fields.
Comma separted value record	More flexible than fixed field records, as there is no character limit to the value of a field.

A **simple associative store** will have the **API formal specification**.

```
store: string * string -> unit
retrieve: string -> string option (* either the value stored, or nothing at all *)
```

Definitions

Keyword	Meaning
Value	What is being stored.
Field	A place to hold a value.
Schema	A strongly typed specification of the database.
Key	The field(s) used to locate a record.
Index	A derived structure used to quickly find relevant record.
Query	A lookup function.
Update	A modification of data.
Transaction	An atomic change of a set of field.

An update is often implemented as a transaction.

Abstraction and Interfaces

We hope to have a fairly narrow interface that can map onto many operations. In an ideal world:
- All operations are done through the interface.
- The interface never change.

But in real world, large database projects are often a mess, and fixing the mess sometimes requires changing the interface. Changing interfaces break applications!

Logical Arrangement of a Database

The **DBMS** uses the **disc drive**, which is an abstraction over the **secondary storage**. This gives a consistent, nonchanging API which applications can use.

This API is often in form of SQL queries, SQL injection is an example of insecurity in the interface.

Operating System View of a Database

The **DBMS** is a process running in userspace.
- An **application** communicates with the **DBMS** through **kernel space communication**.
- Then the **DBMS** use **kernel space drivers** to access the **DBMS**.

An alternative implementation have the **DBMS** access a non-OS partition directly.

Data can be stored in primary store, secondary store, or distributed.

Definition
Big data is data too big to fit in primary store.

DBMS Operations

Operation	Description
Create	Insert new data
Read	Query the database
Update	Modify objects in the database
Delete	Remove data

Management Operations

- Create/change schema
- Create views
- Indexing/stats generation
- Reorganise data layout and backups

Amount of Writing

Database implementation choice depends on the amount of writing.

- A database can have a lot of lookups but rarely changes (e.g. library catalogue).
- **Transaction optimised**: concurrent queries and updates, they will affect the consistency of reads.

Definition
Atomicity is where changes are apparent to all users at once. An overhead is needed to achieve this.

- **Append only journal**: inverse of a transaction optimised DB, data is never updated.

Consistency Checks

Consistency rules includes value range check, foreign key referential integrity, value atomicity (all values are atomic), entity integrity (no missing fields).

Types of Databases

Relational Database

Consists of 2D tables.

- One row per record (a.k.a. a tuple), each with a number of fields.
- A table can have a schema.
- The ordering of the fields are unimportant.

Distributed Databases

Database can be spread over multiple machines.

Benefit	Description
Scalability	Dataset may be too large for a single machine.
Fault tolerance	Service can survive the failure of some machines.
Lower latency	Data can be located closer to the users.

Downsides: overhead after an update to provide a consistent view.

Keyword	Meaning
Consistency	All reads return data that is up to date.
Accessibility	All clients can find some replica of the data.
Partition tolerance	The system continues to operate despite arbitrary message loss or failure of parts of the system.

It is impossible to achieve all 3 in a distributed database. *(why?)*

System that offers **eventual consistency** will eventually reach a consistent state once activity ceases.

ER Model

ER model is an implementation independent technique of describing the data we store in a database.

Definitions

Keyword	Meaning	Symbol
Entity	Model things in the real world	Rectangle
Attributes	Represent properties	Oval
Key	Uniquely identifies an entity instance.	Underline

A key can be **composite**. Examples of **natural keys** are a person's name and nation ID unumber. They may not be unique, it is often better to use a **synthetic key** - beware of using keys that are out of your control.

Definition
A **synthetic key** is auto-generated by the database and only has meaning within the database.

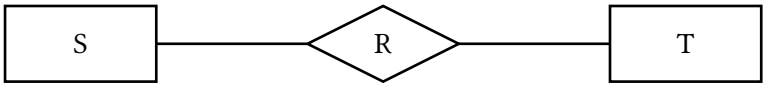
The **scope** of the model is the limited subset of all the real world attributes of the object.

Relationship Cardinalities

Many-to-many Relationships

- Represented in undecorated lines.
- Any S can be related to 0 or more T.
- Any T can be related to 0 or more S.

Note relations can also have attributes.



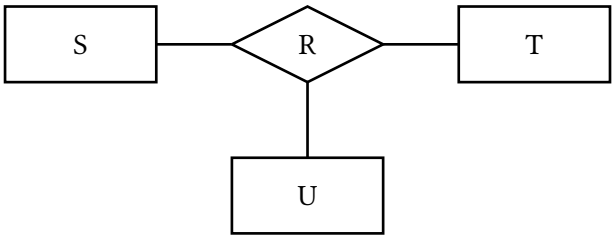
Rules for Modelling

- An attributes exists at most once for any entity or relation.
- Rule of atomicity: every value in a box must be atomic (a.k.k. 1NF)

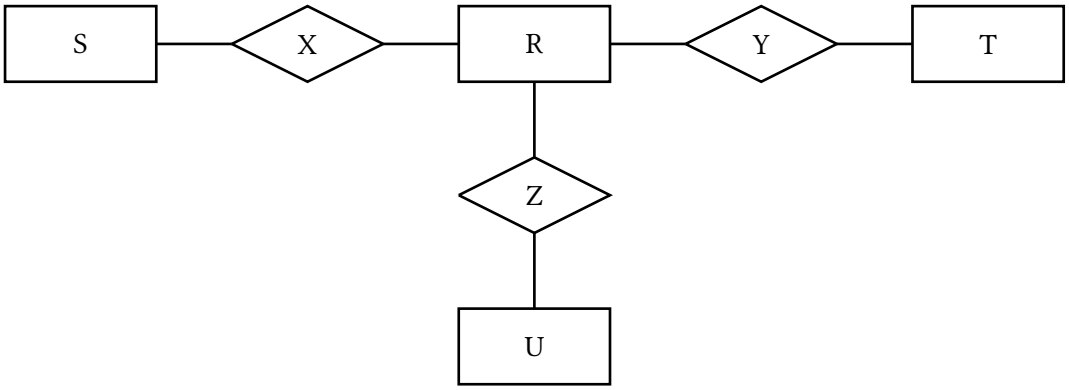
Do not put a comma separated list in the value, more likely than not we will need to break up the list again when searching, which requires text processing.

Tenary Relationships

They may be appropriate, depending on use.



What about 3 binary relationships?



Which one is appropriate depends on the situation, each entity should represent a real world object.

- **Many-to-one** relationships are denoted by an arrow towards the one end.
- **One-to-one** relationships are denoted by two arrow, one at each end.

If R is both many-to-one and one-to-many between S and T, it is one-to-one between S and T.

Definition
A **bijection** is where every member in one set is related to one member of the other set.

One-to-one cardinality doesn't mean one-to-one correspondence: not all elements in S are related to an element in T.

Weak Entity

Definition
The **weak entity** cannot exist without the **strong entity** existing.

- E.g. an alternative title (weak) for a movie (strong).
- Has **discriminators**, not keys. Combined with the **key** from the strong entity uniquely defines the weak entity.

Entity Hierarchy (OO-like)

- Subentities inherit the attribues and relations of the parent entity.
- Multiple inheritance is possible.
- We represent the relation with an *IS A* relation (upside down triangle in diagram).

The Relational Model

Before the relational model, you need to know about the data's low level representation to write a database application.

- We give the user a model of data and language for manipulating the data that is independent of the implementation details.
- The model is based on mathematical relations.

Mathematical Relations

Definitions

- The **cartesian product** is the set of all possible pairs.

$$S \times T = \{(s,t) \mid s \in S, t \in T\}$$

- A **binary relation** of $S \times T$ is any set R with

$$R \subseteq S \times T$$

- R is a **binary relation**.
- S and T are referred to as **domains**.

We are interested in finite relations R that are explicitly stored in a database, which *does not include* infinite relations like the modulus. (e.g. $6 \bmod 5 = 1$)

N-ary Relations

If we have n domains, then n-ary relation R is the set

$$R \subseteq S_1 \times S_2 \times \cdots \times S_n = \{(s_1, s_2, ..., s_n) \mid s_1 \in S_1, s_2 \in S_2, ..., s_n \in S_n\}$$

Definition

Tabular presentation of a relation is where each tuple has a column number.

1	**2**	**...**	$\boldsymbol{n}$
a_1	b_1	...	x_1
a_2	b_2	...	x_2
a_3	b_3	...	x_3
a_4	b_4	...	x_4

Named Columns

Because referring to tuples by column number is annoying.

- Associate an attribute name A_i with each domain in S_i.
- Use records instead of tuples.

Definition

A **database relation** is the finite set

$$R \subseteq \{\{(A_1, s_1), (A_2, s_2), ..., (A_n, s_n)\} \mid s_i \in S_i\}$$

We specify R's schema as $R(A_1 : S_1, A_2 : S_2, ...A_n : S_n)$.

Example: Students

Using the schema *Students(name: string, sid: string, age: integer)*:

```
Students = {
  { (name, "sirius"), (sid: "12345"), (age: 19) }
}
```

Query Language

- The input of a query language is a collection of relatin instances $R_1, R_2, ..., R_k$.
- The output is a single relational instance $Q(R_1, R_2, ..., R_k)$.

We want to create a high level query language Q that is independent of the data, there are many ways to do that.

The Relational Algebra Abstract Syntax

It is generally a tree structure

$Q ::=$

$\mid R$	base relation
$\mid \sigma_{p(Q)}$	selection
$\mid \pi_{x(Q)}$	projection
$\mid Q \times Q$	product
$\mid Q - Q$	difference
$\mid Q \cup Q$	union
$\mid Q \cap Q$	intersection
$\mid \rho_{M(Q)}$	rename

- $p : x \mapsto$ bool is a boolaen predicate.
- $X = \{A_1, A_2, ...\}$ is a vector (a set of attributes).
- $M = \{A_1 \mapsto B_1, A_2 \mapsto B_2, ...\}$ is a list of mappings that takes in one attribute name, and output another attribute name.

Definition
Q is **well formed** if all attribute names of the result are distinct.

- $Q_1 \times Q_2$ requires the subqueries to share no column names.
- $Q_1 \cup Q_2$ requires the subqueries to share all column names.

Mapping RA to SQL

RA is based directly on the underlying set theory.

- Formal semantics/specification works by mapping the query language back to set theory.

Operators

RA	SQL	Notes

$\sigma_{A>12}(R)$	`SELECT DISTINCT *`
	`FROM R`
	`WHERE R.A > 12`
		-

$\pi_{B,C}(R)$	`SELECT DISTINCT B, C` `FROM R`	-
$\rho_{\{B \mapsto E, D \mapsto F\}}(R)$	`SELECT A, B as E, C, D as F` `FROM R`	If we want to swap 2 rows, we will need to rename them one at a time.
$R \cup S$	`(SELECT * FROM R) UNION` `(SELECT * FROM S)`	R and S must have the same schema.
$R \cap S$	`(SELECT * FROM R) INTERSECT` `(SELECT * FROM S)`	
$R - S$	`(SELECT * FROM R) EXCEPT` `(SELECT * FROM S)`	In set theory, $R - S = R \cap (-S)$, but this doesn't make sense on databases, as $-S$ would mean everything that is not in S.

$R \times S$	`SELECT A, B, C, D`
	`FROM R`
	`CROSS JOIN S`
		In set theory, the cartesian product is a set of tuples. In SQL, that tuple is flattened.

Note
The **`DISTINCT`** keyword removes duplicates: each A, B, C, D might be unique, but B, C may be not. Not being distinct is fine in SQL but not fine in set theory as a set contains no duplicates.

The Natural Join

If we ignore domain types and write a relation schema as $R(A)$, where $A = \{A_1, A_2, ...\}$.

- $R(A, B) = R(A \cup B)$ assumes $A \cap B = \emptyset$
- $u.[A] = v.[A]$ means $u.A_1 = v.A_1 \wedge u.A_2 = v.A_2 \wedge ....$
  - For the fields specified, the two records completely agree with each other.

For $R(A, B)$ and $S(B, C)$, define the natural join $R \bowtie S$.

$$R \bowtie S = \{\ t \mid (\exists u \in R, v \in S)\ u.[B] = v.[B],\ t = u.[A] \cup u.[B] \cup v.[C]\ \}$$

```
SELECT *
FROM R
NATURAL JOIN S
```

- If `NULL` values exists, then equality gets more complicated (how?), there are further variations of natural joins (left/right/inner/outer).
- If we want to use a custom predicate, use `WHERE` instead of `NATURAL`.

Relational Data Model

How do we store data in a table?

Data Redundancy

One approach is to store everything in one big table.

A big table is a redundant data representation, and redundancy can lead to inconsistencies.
(Example: movies database)

- We should be able to insert a person without knowing his role in a film.
- If we delete all films about a director, we lose information about the director.
- If a director's name is mispelled, we need to update it for all films.

Rule
Rule for removing **data redundancy**: store one fact in one place.

It also cause performance issues:

- To maintain consistency for every user, a simple transaction involves many things to do.
- Many records have to be locked to maintain atomicity, so it is less concurrent than it could be.

Breaking down tables reduces redundancy, but we will need to do joins which is expensive.

- The naive implementation requires doing a cartesian product, which has quadratic time.
- Actual database implementations uses heuristics to reduce time complexity.

Rule
The record should semantically depend on the key.

E.g. timestamp of birth should not be used as the key for a person, as a person's name does not depend on the timestamp.

An **all key table** is needed to store a many-to-many relation.

Relational Keys

Definition
A **relational key** is a unique handle on a record.

Let $R(X)$ is a relational schema and $Z \subseteq X$. If for any record u and v:

$$u[Z] = v[Z] \implies u[X] = v[X]$$

Then Z is a **superkey** of R.

If no proper subset of Z is a key for R, then Z is a **key** for R. Then for $R(Z \cup Y)$, we write

$$R(\underline{Z}, Y)$$

Foreign Key

Suppose we have $R(Z, Y)$, let $S(W)$ be a relational schema where $Z \subseteq W$. We say Z represents a foreign key in S for R if for any instance

$$\pi_Z(S) \subseteq \pi_Z(R)$$

Think of the foreign key as a pointer.

A foreign key is denoted with an overline.

Definition
A database has **referential integrity** when all foreign key constrains are satisfied.

Simplifying Relations

We can combine tables together using **type tags** to reduce the number of tables.

Before	After
$R\big(\underline{X, Z}, U\big)$	$RQ\big(\underline{X, Z, \text{type}}, U, V\big)$
$Q\big(\underline{X, Z}, V\big)$	Where $\text{type} = \{u, v\}$.

Notice all attributes are still semantically dependent on the key.

- Advantage: one less table, so less joins needed.
- Disadvantage: if a record does not have a relation, then the field storing the attribute will be `NULL`.