Information Systems (Informationssysteme)

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Part IV

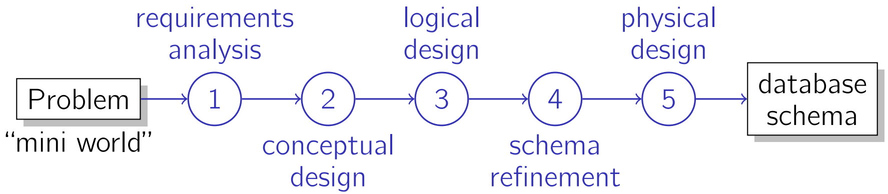
Database Design

Database Design Process

Database systems are very good at handling your data. . .

. . . once your data is in a form that can be digested by the system.

How do we get from a real-world problem to a database schema?



1. **requirements analysis** — Meet with customers, understand their problem.
2. **conceptual design** — Develop a high-level model for the data that should be stored in the database, typically using an **ER diagram**.

Database Design Process (cont.)

3. **logical design** — Convert the conceptual design into the data model of the chosen DBMS. Result is a **conceptual schema** ($\nearrow$ slide 17).
4. **schema refinement** — Refine obtained conceptual schema, *e.g.*, using **normalization** (see later).
5. **physical design** — Develop a physical schema that meets the application's performance needs.

Note: In practice, you'll have to re-iterate some or all of these steps multiple times until you reach a satisfactory design.

Requirements Analysis

Main Goal: Understand user's needs.

- **Meet and discuss** with user groups; **study** existing documentation and/or applications.
- **Listen** and watch out for real-world **entities** that should be reflected in the database and how they **relate** and interact with each others.
- Make sure you **understand** the user's needs:
  - **Note down** your understanding in a way that you can discuss with your users (informal notation; prose text).
  - **Re-iterate** with users to make sure your understanding matches the needs of the users.

Requirements Analysis

"As one of the largest cocktail bars in town, we are really proud of our large collection of cocktail recipes. For each cocktail (recipe) we would like to store its name, a short description, instructions how to make the cocktail, and an information how long that cocktail is already in our database. Each cocktail consists of a number of ingredients, which have a name, a short textual characterization of their flavor, and an information about the amount of alcohol they contain.

It is also important to know which supplier offers which of the ingredients (and at which price). Our supplier list contains addresses and URLs for each supplier. Sometimes, we even know a direct contact person that belongs to a supplier, including his/her name, phone number, and email address."

Requirements Analysis

Rule of thumb:

- Mark **subjects** in a customer's description that describe **concepts** (or "entities") that should be stored in the database.
    - *E.g.*, **cocktails** (or recipes) and **ingredients** should be stored in the database.
- Mark **verbs** that indicate **relationships** between concepts.
    - *E.g.*, cocktails **consist of** ingredients (or: ingredients **are contained in** cocktails).
- In addition, watch out for **attributes** that further characterize a concept/entity.
    - *E.g.*, **name**, **description**, etc. characterize cocktails; **name**, **flavor**, and **alcohol percentage** characterize ingredients.

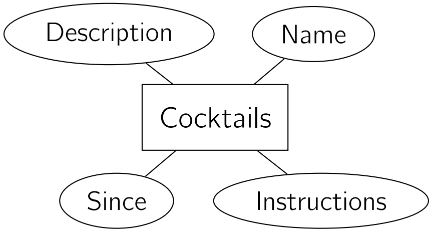
Conceptual Design: ER Model

Conceptual Database Design:

- High-level description of data to be stored in database.
- Typically uses a rather **formalized notation**.
  - → Typically: **Entity-Relationship Model (ER Model)** and **ER Diagrams**.
  - → Clear notation, yet **independent** of the data model used by the specific database system.
- The ER Model helps to
  - **communicate** with users (and verify the model) and
  - **translate** into a conceptual schema for the used DBMS.
    (We will learn rules how, *e.g.*, an ER Diagram can mechanically be translated into a relational database schema.)

ER Model: Entity Sets

- An **entity** is an object in the real world that is distinguishable from other objects.
- An **entity set** is a collection of similar entities.
- We represent an entity set in an ER Diagram as a **rectangle**.



- An entity is described using a set of **attributes**.
- We use **ellipses** to represent attributes.

Attribute Domains

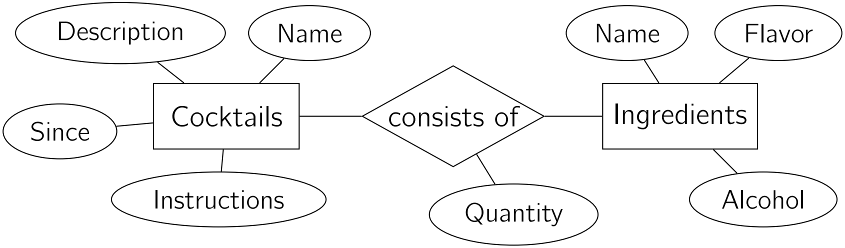
The **domain** of an attribute describes its **possible values**.

E.g.,

- Name: *strings of length 30*
- Description: *strings of length 200*
- Since: *date value greater than Jan 1, 1970*
- Instructions: *strings of length 500*

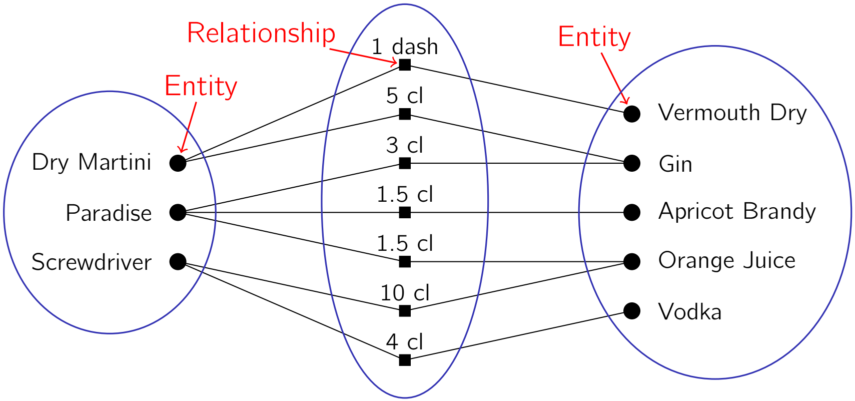
ER Model: Relationship Sets

- A **relationship** is an association among two (or more) entities.
- A **relationship set** is a collection of similar relationships.
- We represent relationship sets as **diamonds**.



- Relationships can carry **attributes**, too.

Entities, Relationships, and Sets Thereof



Entity Set
Cocktails

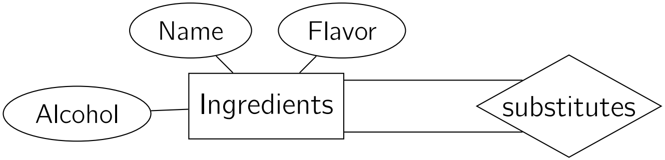
Relationship Set
Consists of

Entity Set
Ingredients

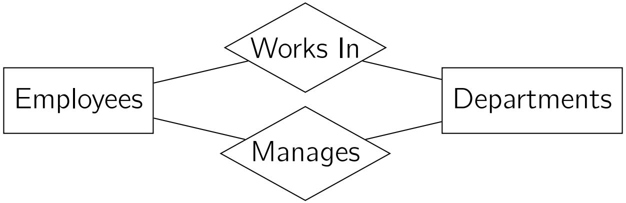
More Relationships

Relationships can also associate two entities within the **same** entity set.

E.g., some ingredients can be substituted by another one (when an ingredient has run out of stock):

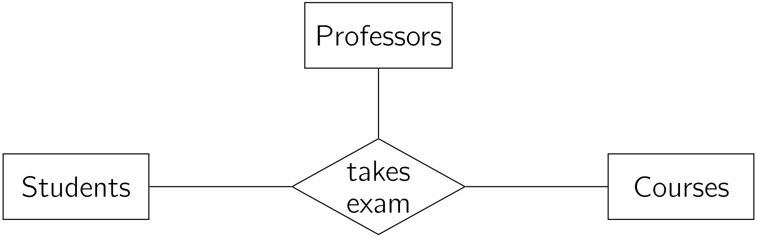


And there can be **multiple** relationship sets between the same entity sets:



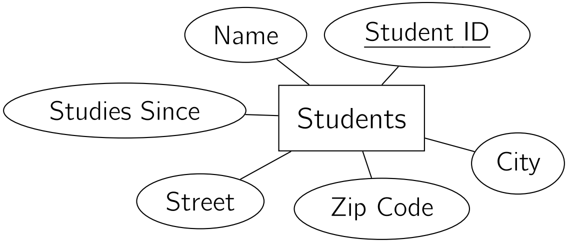
n-Ary Relationships

Relationships can be *n*-ary:



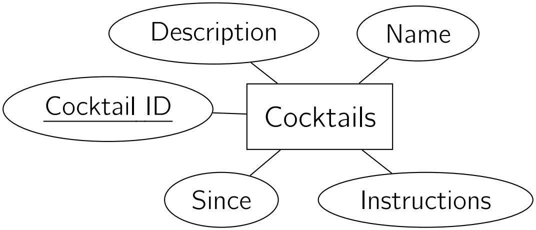
Attributes and Keys

- Generally, an entity is **uniquely identified** by the values of its attributes.
- Sometimes, a **subset** of attributes is enough to uniquely identify an entity.
  - → *e.g.*, Student ID; SSN; course number + semester; etc.
- We call a minimal set of identifying attributes a **key**.
- We use underlining to mark the (set of) key attributes.



Attributes and Keys

- If there is no simple identifying (set of) attribute(s), it is often useful to introduce an **artificial key attribute** (*e.g.*, an integer number).



- If there are multiple **candidate keys**, typically one is designated to be the **primary key**.
  (Having a simple, designated key also eases translation to relational algebra, which we will look at later.)

Keys for Relationships?

✎ **What about keys for relationships?**

Participation Constraints

Very often, the participation of entities in a relation set can be further constrained:

- Each cocktail consists of **at least one** ingredient.
- A contact person for a supplier is **optional**. But there must be **at most one** contact person per supplier.

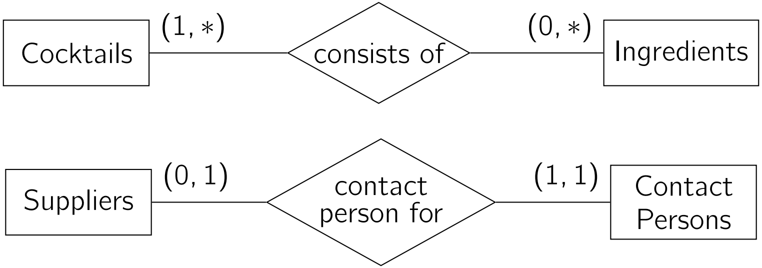
In other words:

- In the **consists-of** relationship set,
  - each **cocktail** participates $1..\infty$ times,
  - each **ingredient** participates $0..\infty$ times.
- In the **contact-person-for** relationship set,
  - each **supplier** participates 0..1 times,
  - each **contact person** participates 1 time.

Participation Constraints: (*min*, *max*) Notation

Use (*min*, *max*) **notation** to specify such constraints.

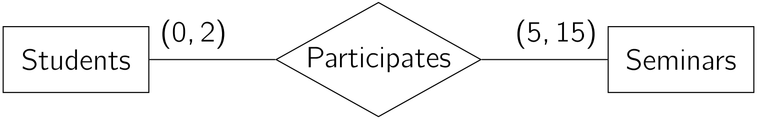
→ Specifiy **minimum and maximum number of times that each entity may participate** in the relationship set.



Typically: Use '$*$' instead of '∞'.

(*min*, *max*) Notation

- 0, 1, and $*$ are certainly seen most often in ER Diagrams.
- But other values can make sense, too.

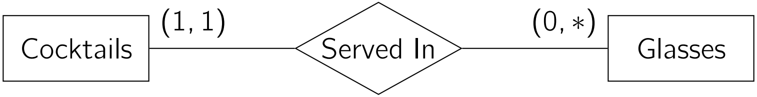


✎ **Describe the meaning of these constraints in natural language.**

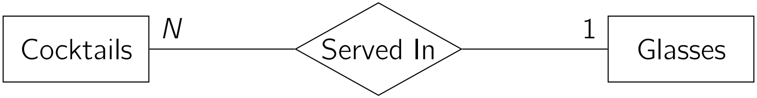
Alternative Notation

An alternative, often-seen notation is to label relationship sets as either $1 : 1$, $1 : N$ (or $N : 1$), or $N : M$.

(min, max) notation:



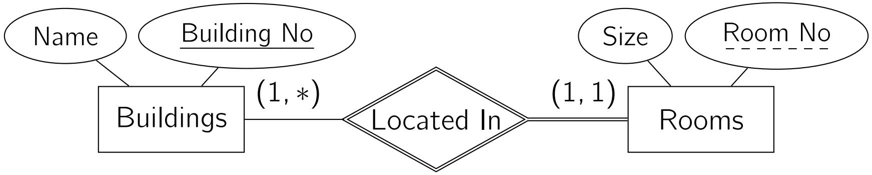
Alternative:



The semantics *"one type of glass can be used for N different cocktails"* is counter-intuitive to that of the (min, max) notation!

Advanced Concepts: Weak Entities

- **“Weak entities”** are entities that can exist only in combination with a **“strong entity”**.

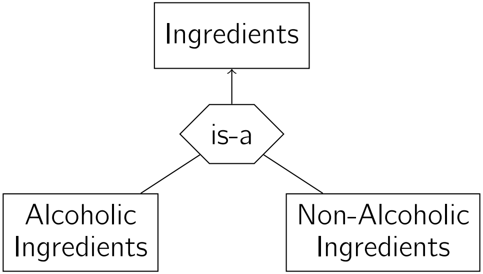


- Since weak entities depend on their “strong” counterpart, they do not themselves have a unique key.
  - → Use key of partner to form a complete key.
  - → Here: ⟨Building No, Room No⟩ together identify a room.

Advanced Concepts: Generalization/Specialization

Generalization Factor out common characteristics to build a common "supertype."

Specialization Derive new, specialized entity sub-types, possibly by adding new characteristics (such as new attributes).

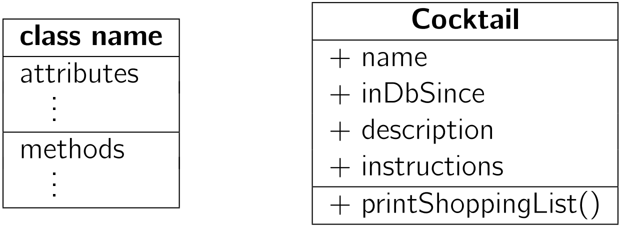


There is no real standard notation to express generalization/specialization.

ER Model ↔ UML

The **Unified Modeling Language (UML)** has emerged as a modeling language for a wide range of design tasks.

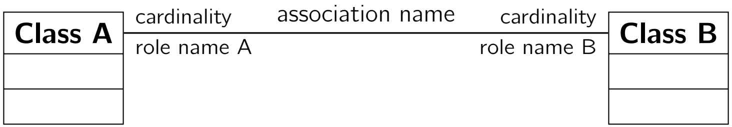
- In UML, **class diagrams** are closest to ER Diagrams.
- Unlike entity sets in the ER, UML classes can contain **methods**.



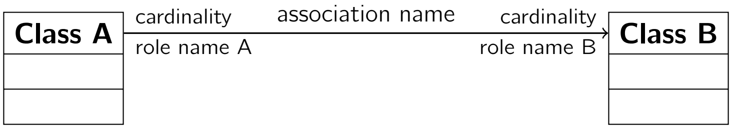
- UML is more intended for (in-memory) application design. Entities/objects are, therefore, identified via **pointers**, not through explicit **key attributes**.

UML Associations

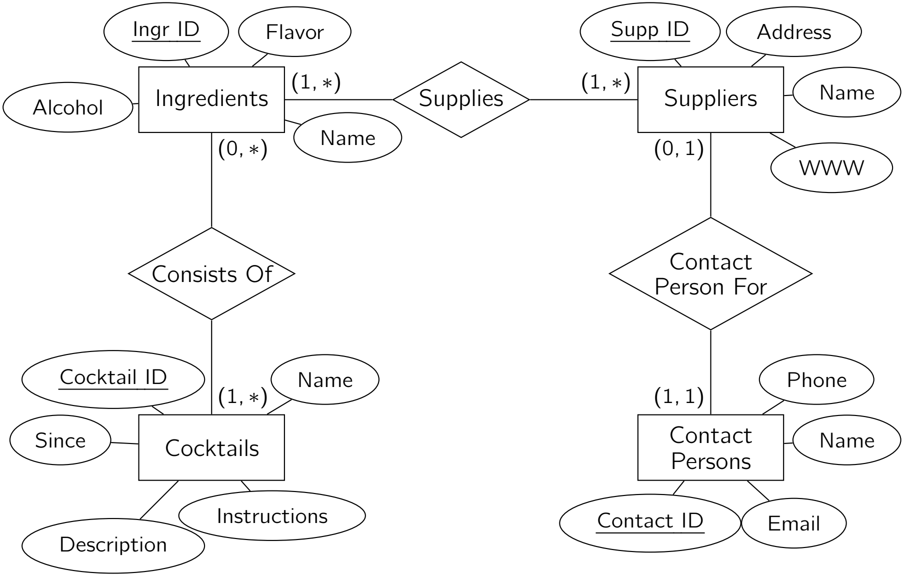
UML associations take the role of relationship sets in ER Models.



Often, associations are **directed**:



$\rightarrow$ Can navigate from object to object only in one direction then.

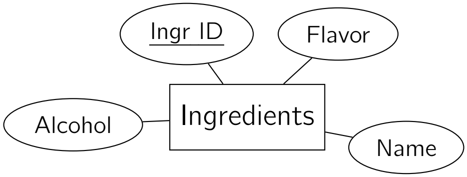


Remaining question: How can we turn that into a database schema?

From an ER Diagram to a Relational Schema

Mapping an **entity set** into a relation is straightforward.

→ Each attribute of the entity set becomes an attribute of the table.



↓

Ingredients			
<u>IngrID</u>	Name	Alcohol	Flavor
⋮	⋮	⋮	⋮

Relations and Keys

Observe that we use the concept of **keys** also in the relational world.

- A **minimal set of fields** that **uniquely identifies a tuple (row)** in a table is called a **(candidate) key**.
  - $\rightarrow$ In **any legal instance** of the relation, two distinct tuples cannot have identical values in all the fields of a key.
  - $\rightarrow$ No subset of the key is a unique identifier for a tuple.

> The **key constraint** is a property of the **schema**. A column that just happens to contain unique values in the current table **instance** is **not** a key.

- Again, among multiple candidate keys, we typically select one **primary key**.

Key Constraints

In database systems, keys can be declared together with the schema of the table. *E.g.*, in SQL:[5]

```
CREATE TABLE Ingredients ( IngrID   INTEGER NOT NULL,
                           Name     CHAR(30),
                           Alcohol  DECIMAL(3,1),
                           Flavor   CHAR(20),
                           PRIMARY KEY (IngrID) )
```

The DBMS will enforce such constraints and reject any modifications that would violate the key constraint.

[5]Fields marked as `NOT NULL` cannot be left blank for any row; key columns must be declared `NOT NULL`. `DECIMAL(`m`,`n`)` is a decimal number type with m digits total and n digits after the decimal.

Relationships in the Relational World

An *n*-ary **relationship** in the ER Model is an ***n*-tuple** of entities.

That is, the corresponding **relationship set** can be thought of as the set

$$\{\,(e_1,\ldots,e_n) \mid e_1 \in E_1,\ldots,e_n \in E_n\,\}$$

(ignoring relationship attributes for a moment).

We **could** use that representation to express relationships in the relational world:

ConsistsOf								
CockID	CName	Since	Descr	Instr	IngrID	IName	Alcohol	Flavor
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

- Observe that we re-named the 'Name' fields, because column names must be unique within one table.

Relationships in the Relational World

Such an encoding would incur significant **redundancy** and **storage overhead**.

- *E.g.*, every cocktail redundantly appears at least once in the *ConsistsOf* relation.

Remember that the 'Cocktail ID' already **uniquely determines** all remaining cocktail properties:

$$CockID \rightarrow CName \times Since \times Descr \times Instr \quad .$$

Columns *CName*, *Since*, *Descr*, and *Instr* can thus safely be **omitted** in *ConsistsOf*.

→ When needed, the information can always be **looked up** in *Cocktails* (with help of the *CockID* value).

Relationships in the Relational World

Likewise, we can also omit all non-key columns of *Ingredients*:

ConsistsOf	
CockID	IngrID
⋮	⋮

Let us now put the **relationship attributes** back:

ConsistsOf		
CockID	IngrID	Quantity
⋮	⋮	⋮

Example (and SQL Refresher)

✎ **Assuming** *Cocktails*, *Ingredients*, **and** *ConsistsOf* **are stored in an SQL database, how could we re-construct the original, full** *ConsistsOf* **relation?**

Foreign Keys

Such “lookups” occur very often in relational databases.

- The concept is, in fact, a **corner stone** of relational databases.
- Columns *CockID* and *IngrID* in *ConsistsOf* are called **foreign keys**. They **refer to** *Cocktails* and *Ingredients* (respectively).

Foreign keys can be declared in SQL, too:

```
CREATE TABLE ConsistsOf (
     CockID INTEGER NOT NULL,
     IngrID INTEGER NOT NULL,
     FOREIGN KEY (CockID) REFERENCES Cocktails,
     FOREIGN KEY (IngrID) REFERENCES Ingredients )
```

→ Foreign keys refer to the **primary key** of the respective relation.

Foreign Keys

- Relational database systems use **regular, user-accessible attribute values** to reference between tuples.
  $\rightarrow$ No "pointers" or other internal data structures.
- Remember **physical data independence**:
  - Tuples can freely be moved to new locations in memory/on disk without breaking tuple associations.
- Foreign key references can always be "followed"[6] in **both** directions.

[6] SQL is declarative and does not really offer navigation primitives.

Relationships and Keys

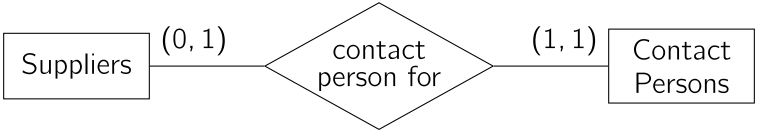
✎ **Which columns form a key in *ConsistsOf*?**

ConsistsOf		
CockID	IngrID	Quantity
⋮	⋮	⋮

Does *ConsistsOf* have a key at all?

Participation Constraints

For some relationship sets we know that an entity may appear **at most once** in the set:



The respective columns in the resulting relation thus must be **keys**.

Here:

- *SuppID* is a key candidate in the *ContactPersonFor* relation.
- *ContactID* is a key candidate in the *ContactPersonFor* relation.

Merging Relations

Tables that have the **same key** can be **merged** into one:

Cocktails		
CockID	Name	$\cdots$
$\vdots$	$\vdots$	$\ddots$

ServedIn	
CockID	GlassID
$\vdots$	$\vdots$

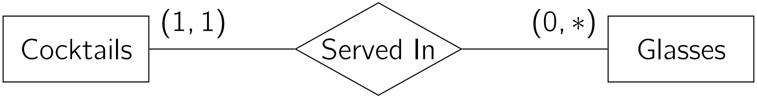
$$\searrow \text{merge} \swarrow$$

$$\downarrow$$

Cocktails			
CockID	Name	$\cdots$	GlassID
$\vdots$	$\vdots$	$\vdots$	$\vdots$

Participation Constraints

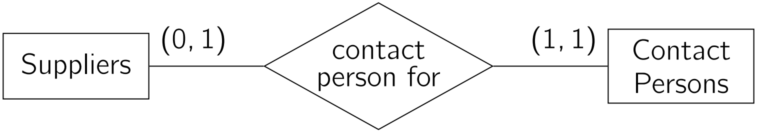
✎ **Which of the participation constraints in**



does the merged relation implement?

Merging Relations

For 1 : 1 relationships, there are various options to merge relations:



1. No relations could be merged.
2. *ContactPersons* could be merged with *ContactPersonFor*.
3. *Suppliers* could be merged with *ContactPersonFor*.
4. All three relations could be merged into one.

Merging Relations

Suppose we chose option 3:

Suppliers				
<u>SuppID</u>	Name	Address	WWW	ContactID
⋮	⋮	⋮	⋮	⋮

(where *ContactID* is a **foreign key** on the *ContactPersons* relation).

What if there is **no contact person** for a given supplier?

- In such a case, we'd want to leave the *ContactID* **empty**.
- This can be done by setting *ContactID* to **null**.

Null Values

Null values play an important role in relational databases.

They are used to model a variety of real-world scenarios:

- A value exists (in the real world), but is **not known**.
  - → A supplier might have a *WWW* URL, but we don't know it.
- **No value exists**.
  - → A supplier might not have a *WWW* URL.
- The attribute is **not applicable** for this tuple.
  - → In a *Persons* relation, the *Semester* field only applies to students.
- . . .

Null is a **special value**, distinct from **any other value** in the column's domain.

→ **Null** is **not** the numeric value 0 and **not** the empty string.

Behavior of Null Values

In operations and predicates, think of **null** as **“unknown”**:

and	true	unknown	false
true	true	unknown	false
unknown	unknown	unknown	false
false	false	false	false

or	true	unknown	false
true	true	true	true
unknown	true	unknown	unknown
false	true	unknown	false

- **Arithmetic operations** with **null** evaluate to **null** (**null** $+ 42 \multimap$ **null**).
- **Comparisons** with **null** evaluate to **null** ($\mathit{Semester} <$ **null** $\multimap$ **null**).

✎ Exercise to try at home in SQL: Given the “Presidents” database used in the lecture, find all presidents that are still alive (*i.e.*, their `DEATH_AGE` is set to `NULL`).

Null Values in SQL

In SQL, null values are expressed using the keyword `NULL`:

```
INSERT INTO Suppliers VALUES
  (4711, 'Shop Rite', '31 Main St', NULL, NULL)
```

Null values can be allowed or disallowed for particular columns.

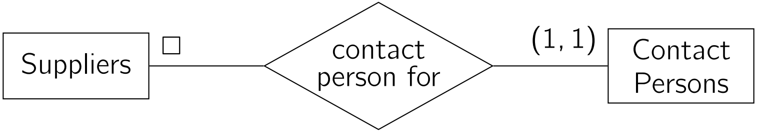
→ See SQL example on slide 67.

→ Key columns must not contain null values.

Null Values and Participation Constraints

The allowance of null values is another knob to restrict **participation constraints** in the relational world.

E.g., ContactPersonFor:



Column *ContactID* in relation *Suppliers*:

$$\begin{aligned}\texttt{NULL}\ \text{(null values allowed)} &\Rightarrow \Box \equiv (0,1)\\ \texttt{NOT NULL}\ \text{(null values disallowed)} &\Rightarrow \Box \equiv (1,1)\end{aligned}$$

By marking *ContactID* in *Suppliers* as a **key**, we can further constrain the **maximum participation** of *ContactPersons* in the relationship set.

Translation ER Diagram → Relational Schema

To translate an ER Diagram into a relational schema:

1. Map all **entity sets** to a **relation**.
2. Identify a **primary key** in each resulting **relation**.
3. Map all **relationship sets** to a **relation**.
4. Identify **foreign key** constraints in all those relations.
5. Refine the resulting schema by **merging** relations with **same key**.
   - Often, there is some degree of freedom in that step.
   - (Dis)allow **null values** to reflect **participation constraints**

Generally, **not all** participation constraints can losslessly be modeled with only (foreign) key constraints and constraints on null values.