# Computer Science E-66

## Introduction
## Database Design and ER Models
## The Relational Model

Harvard Extension School

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*Lecture designed by David G. Sullivan*

## Databases and DBMSs

- A *database* is a collection of related data.
  - refers to the data itself, *not* the program
- Managed by some type of *database management system* (DBMS)

## The Conventional Approach

- Use a DBMS that employs the *relational model*
  - use the SQL query language
- Examples: IBM DB2, Oracle, Microsoft SQL Server, MySQL
- Typically follow a client-server model
  - the database server manages the data
  - applications act as clients
- Extremely powerful
  - SQL allows for more or less arbitrary queries
  - support *transactions* and the associated guarantees

## Transactions

- A *transaction* is a sequence of operations that is treated as a single logical operation.
- Example: a balance transfer

*transaction T1*

```
read balance1
write(balance1 - 500)
read balance2
write(balance2 + 500)
```

- Other examples:
  - making a flight reservation
    select flight, reserve seat, make payment
  - making an online purchase
- Transactions are *all-or-nothing*: all of a transaction's changes take effect or none of them do.

## Why Do We Need Transactions?

- To prevent problems stemming from system failures.
  - example:

*transaction*

```
read balance1
write(balance1 - 500)
CRASH
read balance2
write(balance2 + 500)
```

- what should happen?

## Why Do We Need Transactions? (cont.)

- To ensure that operations performed by different users don't overlap in problematic ways.
  - example: what's wrong with the following?

*user 1's transaction*

```
read balance1
write(balance1 - 500)



read balance2
write(balance2 + 500)
```

*user 2's transaction*

```
read balance1
read balance2
if (balance1 + balance2 < min)
    write(balance1 - fee)
```

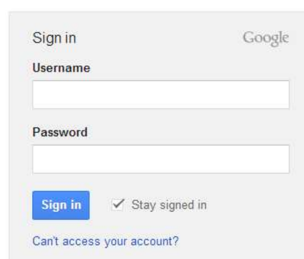
- how could we prevent this?

## Limitations of the Conventional Approach

- Can be overkill for applications that don't need all the features
- Can be hard / expensive to setup / maintain / tune
- May not provide the necessary functionality
- Footprint may be too large
  - example: can't put a conventional RDBMS on a small embedded system
- May be unnecessarily slow for some tasks
  - overhead of IPC, query processing, etc.
- Does not scale well to large clusters

## Example Problem I: User Accounts

- Database of user information for email, groups, etc.
- Used to authenticate users and manage their preferences
- Needs to be extremely fast and robust
- Don't need SQL. Why?



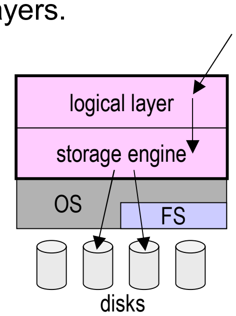

- Possible solution: a key-value store
  - key = user id
  - value = password and other user information
  - less overhead and easier to manage
  - still very powerful: transactions, recovery, replication, etc.

## Example Problem II: Web Services

- Services provided or hosted by Google, Amazon, etc.
- Can involve huge amounts of data / traffic
- Scalability is crucial
  - load can increase rapidly and unpredictably
  - use large clusters of commodity machines
- Conventional relational DBMSs don't scale well in this way.
- Solution: some flavor of noSQL

## What Other Options Are There?

- View a DBMS as being composed of two layers.
- At the bottom is the *storage layer* or *storage engine*.
  - stores and manages the data
- Above that is the *logical layer.*
  - provides an abstract representation of the data
  - based on some data model
  - includes some query language, tool, or API for accessing and modifying the data
- To get other approaches, choose different options for the layers.



## Course Overview

- data models/representations (logical layer), including:
  - entity-relationship (ER): used in database design
  - relational (including SQL)
  - semistructured: XML, JSON
  - noSQL variants
- implementation issues (storage layer), including:
  - storage and index structures
  - transactions
  - concurrency control
  - logging and recovery
  - distributed databases and replication

## Course Requirements

- Lectures and weekly sections
  - sections: optional but recommended; start this week
  - also available by streaming and recorded video
- Five problem sets
  - several will involve programming in Java
  - all will include written questions
  - grad-credit students will complete extra problems
  - must be your own work
    - see syllabus or website for the collaboration policy
- Midterm exam
- Final exam

## Prerequisites

- A good working knowledge of Java
- A course at the level of CSCI E-22
- Experience with fairly large software systems is helpful.

## Course Materials

- Lecture notes will be the primary resource.
- Optional textbook: *Database Systems: The Complete Book* (2nd edition) by Garcia-Molina et al. (Prentice Hall)
- Other options:
  - *Database Management Systems* by Ramakrishnan and Gehrke (McGraw-Hill)
  - *Database System Concepts* by Silberschatz et al. (McGraw-Hill)

## Additional Administrivia

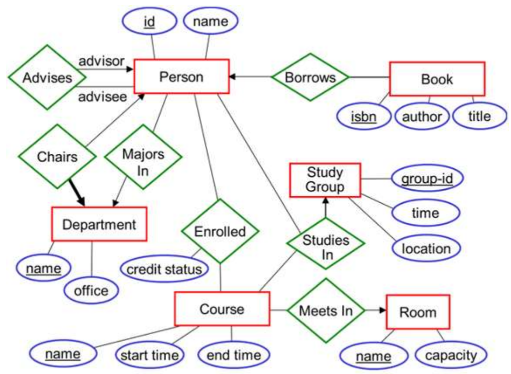
- Instructor: Cody Doucette
- TA: Eli Saracino
- Office hours and contact info. are available on the Web:
  http://cscie66.sites.fas.harvard.edu
- For questions on content, homework, etc.: Ed Discussion

## Database Design

- In database design, we determine:
  - which pieces of data to include
  - how they are related
  - how they should be grouped/decomposed
- End result: a *logical schema* for the database
  - describes the contents and structure of the database

## ER Models

- An *entity-relationship (ER) model* is a tool for database design.
  - graphical
  - implementation-neutral




- ER models specify:
  - the relevant entities (“things”) in a given domain
  - the relationships between them

## Sample Domain: A University

- Want to store data about:
  - employees
  - students
  - courses
  - departments
- How many tables do you think we’ll need?
  - can be hard to tell before doing the design
  - in particular, hard to determine which tables are needed to encode relationships between data items

## Entities: the "Things"

- Represented using rectangles.
- Examples:

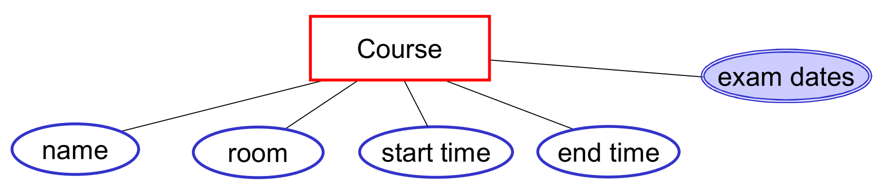
Course | Student | Employee

- Strictly speaking, each rectangle represents an *entity set*, which is a collection of individual entities.

| Course | Student | Employee |
| --- | --- | --- |
| CSCI E-119 | Jill Jones | Drew Faust |
| English 101 | Alan Turing | Dave Sullivan |
| CSCI E-268 | Jose Delgado | Margo Seltzer |
| … | … | … |

## Attributes

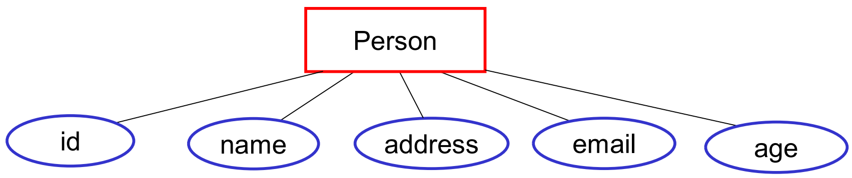
- Associated with entities are *attributes* that describe them.
  - represented as ovals connected to the entity by a line
  - double oval = attribute that can have multiple values



## Keys

- A *key* is an attribute or collection of attributes that can be used to uniquely identify each entity in an entity set.

- An entity set may have more than one possible key.
  - example:




  - possible keys include:

## Candidate Key

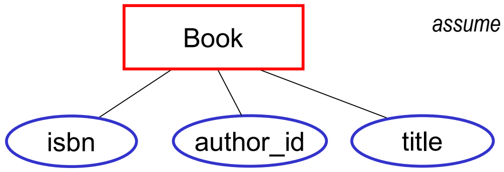
- A *candidate key* is a *minimal* collection of attributes that is a key.
  - minimal = no unnecessary attributes are included
    - *not* the same as *minimum*

- Example: assume (name, address, age) is a key for Person
  - it is a *minimal* key because we lose uniqueness if we remove any of the three attributes:
    - (name, address) may not be unique
      - e.g., a father and son with the same name and address
    - (name, age) may not be unique
    - (address, age) may not be unique

- Example: (id, email) is a key for Person
  - it is *not* minimal, because just one of these attributes is sufficient for uniqueness
  - therefore, it is *not* a candidate key

## Key vs. Candidate Key

- Consider an entity set for books:

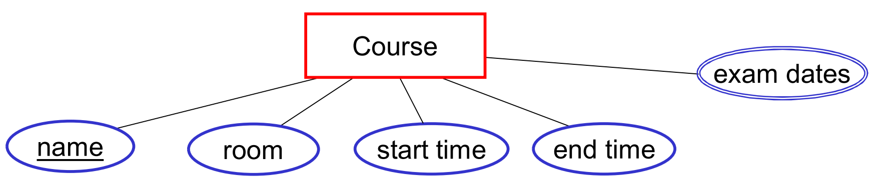



*assume that: each book has a unique isbn*
*an author doesn't write two books with the same title*

| | key? | candidate key? |
|---|---|---|
| isbn | | |
| author_id, title | | |
| author_id, isbn | | |
| author_id | | |

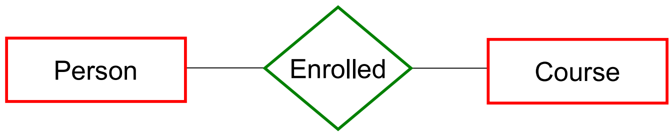
## Primary Key

- We typically choose one of the candidate keys as the *primary key.*
- In an ER diagram, we underline the primary key attribute(s).

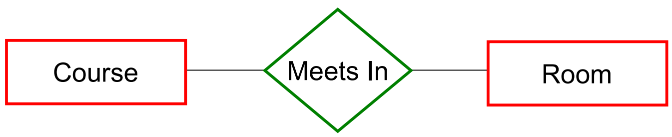


## Relationships Between Entities

- Relationships between entities are represented using diamonds that are connected to the relevant entity sets.
- For example: students are enrolled in courses

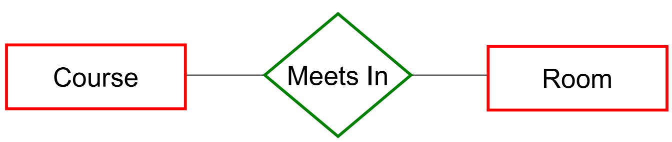


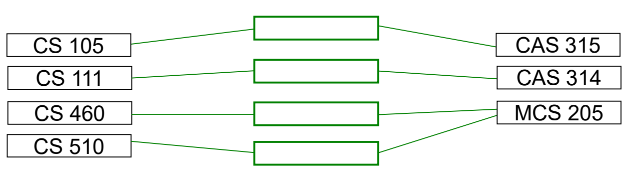

- Another example: courses meet in rooms




## Relationships Between Entities (cont.)

- Strictly speaking, each diamond represents a *relationship set*, which is a collection of relationships between individual entities.

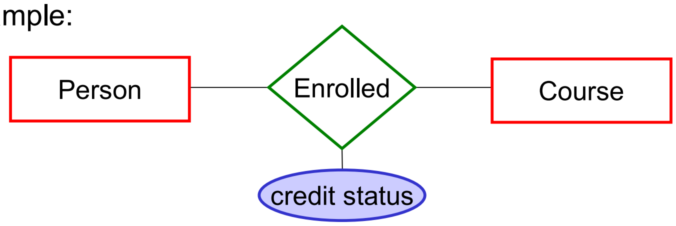



- In a given set of relationships:
  - an individual entity may appear 0, 1, or multiple times
  - a given *combination* of entities may appear at most once
    - example: the combination (CS 105, CAS 315) may appear at most once

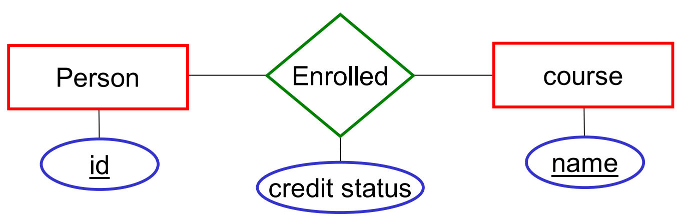
## Attributes of Relationships

- A relationship set can also have attributes.
  - they specify info. associated with the relationships in the set
- Example:




## Key of a Relationship Set

- A key of a relationship set can be formed by taking the union of the primary keys of its participating entities.
  - example: (Person.id, Course.name) is a key of enrolled

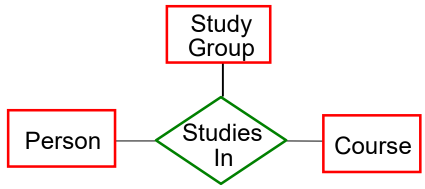



- The resulting key may or may not be a primary key. Why?

## Degree of a Relationship Set

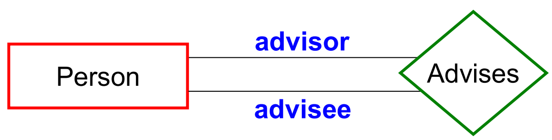
- Enrolled is a *binary* relationship set: it connects two entity sets.
  - degree = 2


- It's also possible to have higher-degree relationship sets.
- A *ternary* relationship set connects three entity sets.
  - degree = 3




## Relationships with Role Indicators

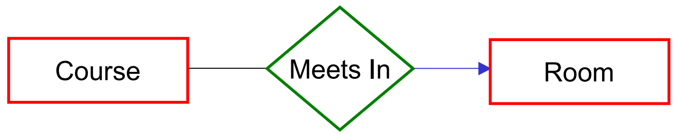
- It’s possible for a relationship set to involve more than one entity from the same entity set.
- For example: every student has a faculty advisor, where students and faculty members are both members of the Person entity set.




- In such cases, we use *role indicators* (labels on the lines) to distinguish the roles of the entities in the relationship.

## Cardinality (or Key) Constraints

- A *cardinality constraint* (or *key constraint*) limits the number of times that a given entity can appear in a relationship set.
- Example: each course meets in *at most one* (i.e., 0 or 1) room

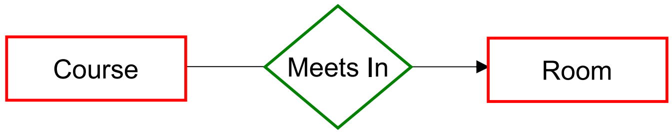



- A key constraint specifies a functional mapping from one entity set to another.
  - each course is mapped to at most one room (course → room)
  - as a result, each course appears in at most one relationship in the *meets in* relationship set
- The arrow in the ER diagram has same direction as the mapping.
  - note: the R&G book uses a different convention for the arrows

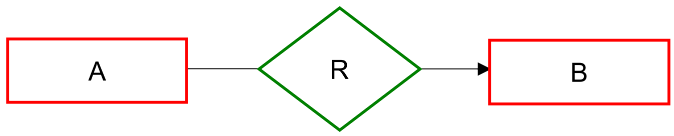
## Cardinality Constraints (cont.)

- The presence or absence of cardinality constraints divides relationships into three types:
  - many-to-one
  - one-to-one
  - many-to-many
- We'll now look at each type of relationship.

## Many-to-One Relationships

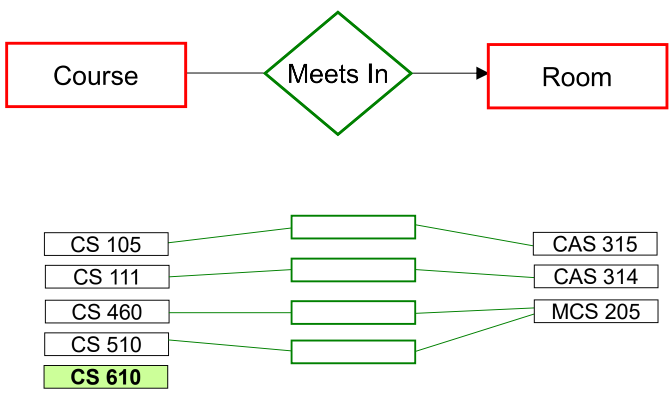



- Meets In is an example of a *many-to-one* relationship.
- We need to specify a *direction* for this type of relationship.
  - example: Meets In is many-to-one from Course to Room
- In general, in a many-to-one relationship from A to B:



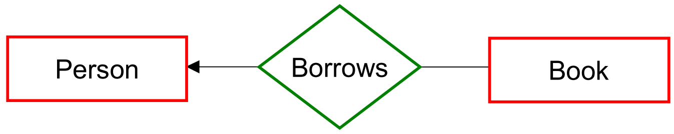

  - an entity in A can be related to *at most one* entity in B
  - an entity in B can be related to an arbitrary number of entities in A (0 or more)

## Picturing a Many-to-One Relationship




- Each course participates in at most one relationship, because it can meet in at most one room.
- Because the constraint only specifies a maximum (*at most one*), it's possible for a course to not meet in any room (e.g., CS 610).

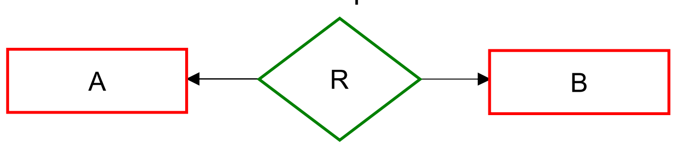
## Another Example of a Many-to-One Relationship



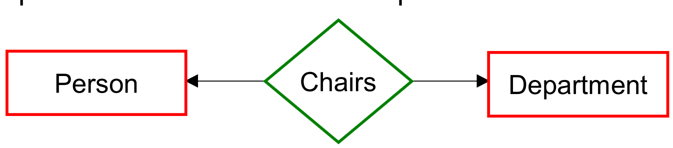

- The diagram above says that:
  - a given book can be borrowed by at most one person
  - a given person can borrow an arbitrary number of books
- Borrows is a many-to-one relationship from Book to Person.
- We could also say that Borrows is a *one-to-many* relationship from Person to Book.
  - one-to-many is the same thing as many-to-one, but the direction is reversed

## One-to-One Relationships

- In a *one-to-one relationship* involving A and B: [not *from* A to B]
  - an entity in A can be related to *at most one* entity in B
  - an entity in B can be related to *at most one* entity in A
- We indicate a one-to-one relationship by putting an arrow on both sides of the relationship:

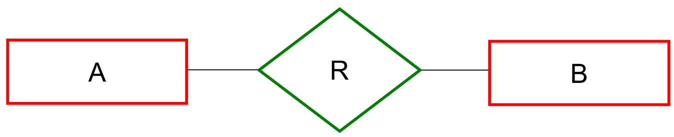



- Example: each department has at most one chairperson, and each person chairs at most one department.

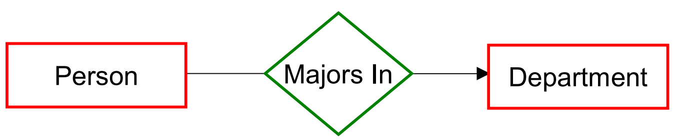


## Many-to-Many Relationships

- In a *many-to-many relationship* involving A and B:
  - an entity in A can be related to an arbitrary number of entities in B (0 or more)
  - an entity in B can be related to an arbitrary number of entities in A (0 or more)
- If a relationship has no cardinality constraints specified (i.e., if there are no arrows on the connecting lines), it is assumed to be many-to-many.

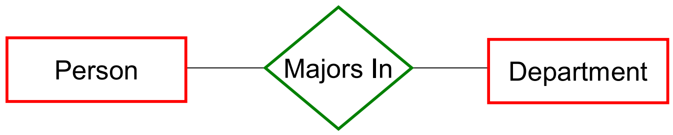



## How can we indicate that each student has at most one major?




- *Majors In* is what type of relationship in this case?

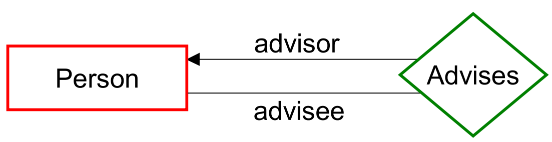
## What if each student can have more than one major?




- *Majors In* is what type of relationship in this case?

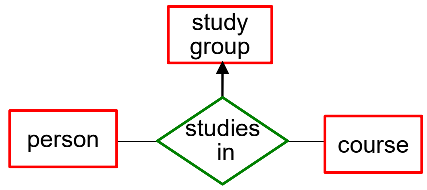
## Another Example

- How can we indicate that each student has at most one advisor?




- Advises is what type of relationship?

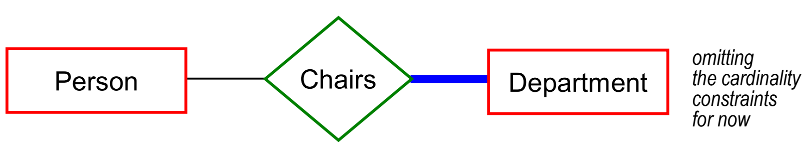
## Cardinality Constraints and Ternary Relationship Sets




- The arrow into "study group" encodes the following constraint: "a person studies in at most one study group *for a given course.*"
- In other words, a given (person, course) combination is mapped to at most one study group.
  - a given person or course can itself appear in multiple studies-in relationships
- For relationship sets of degree >= 3, we use at most one arrow, since otherwise the meaning can be ambiguous.

## Participation Constraints

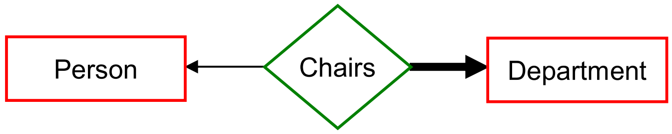
- Cardinality constraints allow us to specify that each entity will appear *at most* once in a given relationship set.
- Participation constraints allow us to specify that each entity will appear *at least* once (i.e., 1 or more time).
  - indicate using a thick line (or double line)
- Example: each department must have at least one chairperson.




- We say Department has *total participation* in Chairs.
  - by contrast, Person has *partial participation*

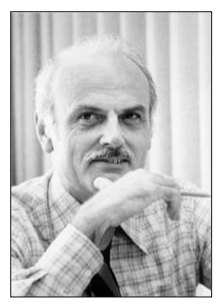
## Participation Constraints (cont.)

- We can combine cardinality and participation constraints.




  - a person chairs at most one department
    - specified by which arrow?
  - a department has ___________ person as a chair

## The Relational Model: A Brief History



- Defined in a landmark 1970 paper by Edgar 'Ted' Codd.
- Earlier data models were closely tied to the physical representation of the data.
- The relational model was revolutionary because it provided *data independence* – separating the *logical* model of the data from its underlying *physical* representation.
- Allows users to access the data *without* understanding how it is stored on disk.

## The Relational Model: Basic Concepts

- A *database* consists of a collection of *tables*.
- Example of a table:

| *id* | *name* | *address* | *class* | *dob* |
|---|---|---|---|---|
| 12345678 | Jill Jones | Canaday C-54 | 2011 | 3/10/85 |
| 25252525 | Alan Turing | Lowell House F-51 | 2008 | 2/7/88 |
| 33566891 | Audrey Chu | Pfoho, Moors 212 | 2009 | 10/2/86 |
| 45678900 | Jose Delgado | Eliot E-21 | 2009 | 7/13/88 |
| 66666666 | Count Dracula | The Dungeon | 2007 | 11/1431 |
| ... | ... | ... | ... | ... |

- Each *row* in a table holds data that describes either:
  - an *entity*
  - a *relationship* between two or more entities
- Each *column* in a table represents one attribute of an entity.
  - each column has a *domain* of possible values

## Relational Model: Terminology

- Two sets of terminology:

| | | |
|---|---|---|
| table | = | relation |
| row | = | tuple |
| column | = | attribute |

- We'll use both sets of terms.

## Requirements of a Relation

- Each column must have a unique name.
- The values in a column must be of the same type (i.e., must come from the same domain).
  - integers, real numbers, dates, strings, etc.
- Each cell must contain a single value.
  - example: we *can't* do something like this:

| ***id*** | ***name*** | ***...*** | ***phones*** |
|---|---|---|---|
| 12345678 | Jill Jones | ... | 123-456-5678, 234-666-7890 |
| 25252525 | Alan Turing | ... | 777-777-7777, 111-111-1111 |
| ... | ... | ... | ... |

- No two rows can be identical.
  - identical rows are known as *duplicates*

## Null Values

- By default, the domains of most columns include a special value called *null*.
- Null values can be used to indicate that:
  - the value of an attribute is unknown for a particular tuple
  - the attribute doesn't apply to a particular tuple. example:

*Student*

| ***id*** | ***name*** | ***...*** | ***major*** |
|---|---|---|---|
| 12345678 | Jill Jones | ... | computer science |
| 25252525 | Alan Turing | ... | mathematics |
| 33333333 | Dan Dabbler | ... | null |

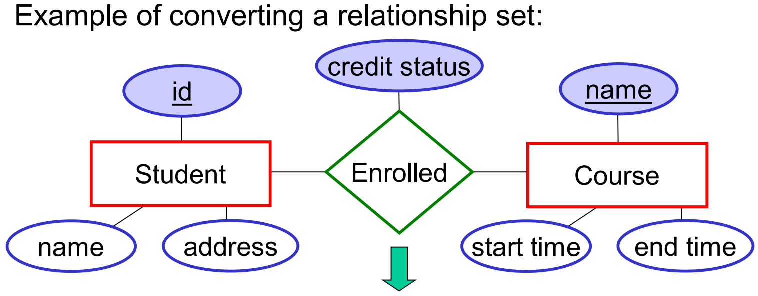
## Relational Schema

- The *schema* of a relation consists of:
  - the name of the relation
  - the names of its attributes
  - the attributes' domains (although we'll ignore them for now)
- Example:

  *Student(id, name, address, email, phone)*
- The schema of a relational database consists of the schema of all of the relations in the database.

## ER Diagram to Relational Database Schema

- Basic process:
  - entity set → a relation with the same attributes
  - relationship set → a relation whose attributes are:
    - the primary keys of the connected entity sets
    - the attributes of the relationship set
- Example of converting a relationship set:

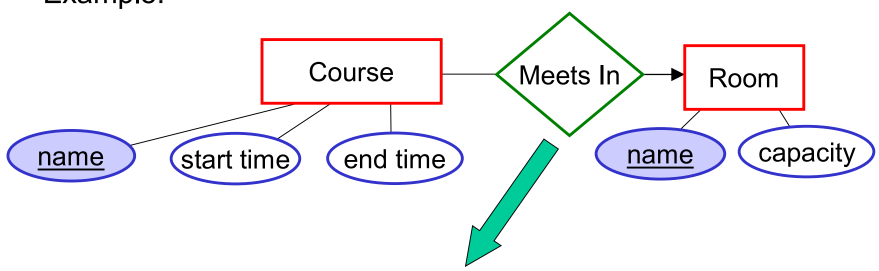



*Enrolled(id, name, credit_status)*

  - in addition, we would create a relation for each entity set

## Renaming Attributes

- When converting a relationship set to a relation, there may be multiple attributes with the same name.
  - need to rename them
- Example:



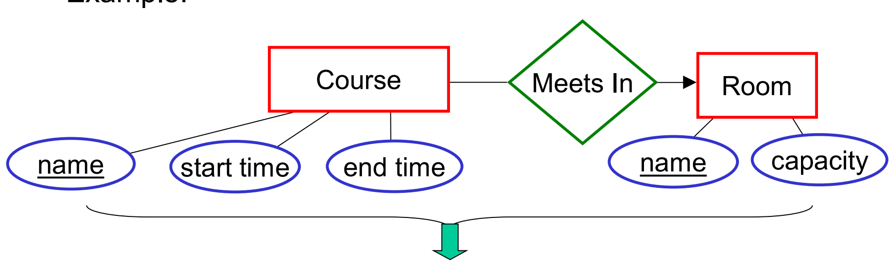

*MeetsIn(name, name)*

*MeetsIn(course_name, room_name)*

- We may also choose to rename attributes for the sake of clarity.

## Special Case: Many-to-One Relationship Sets

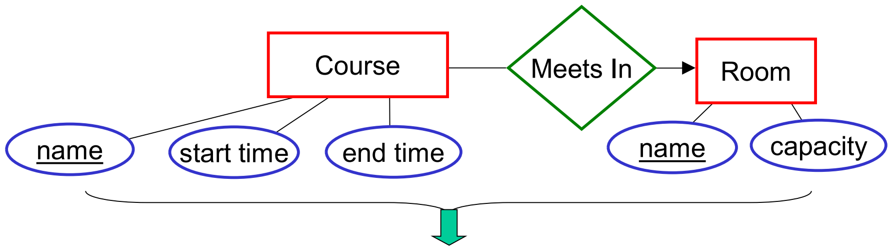
- Ordinarily, a binary relationship set will produce three relations:
  - one for the relationship set
  - one for each of the connected entity sets
- Example:




*MeetsIn(course_name, room_name)*
*Course(name, start_time, end_time)*
*Room(name, capacity)*

## Special Case: Many-to-One Relationship Sets (cont.)

- However, if a relationship set is many-to-one, we often:
  - eliminate the relation for the relationship set
  - capture the relationship set in the relation used for the entity set on the *many* side of the relationship




~~*MeetsIn(course_name, room_name)*~~
*Course(name, start_time, end_time, room_name)*
*Room(name, capacity)*

## Special Case: Many-to-One Relationship Sets (cont.)

- Advantages of this approach:
  - makes some types of queries more efficient to execute
  - uses less space

Course

| *name* | *...* |
|---|---|
| cscie50b | |
| cscie119 | |
| cscie160 | |
| cscie268 | |

MeetsIn

| *course_name* | *room_name* |
|---|---|
| cscie50b | Sci Ctr B |
| cscie119 | Sever 213 |
| cscie160 | Sci Ctr A |
| cscie268 | Sci Ctr A |

Course

| *name* | *...* | *room_name* |
|---|---|---|
| cscie50b | | Sci Ctr B |
| cscie119 | | Sever 213 |
| cscie160 | | Sci Ctr A |
| cscie268 | | Sci Ctr A |

## Special Case: Many-to-One Relationship Sets (cont.)

- If one or more entities don't participate in the relationship, there will be null attributes for the fields that capture the relationship:

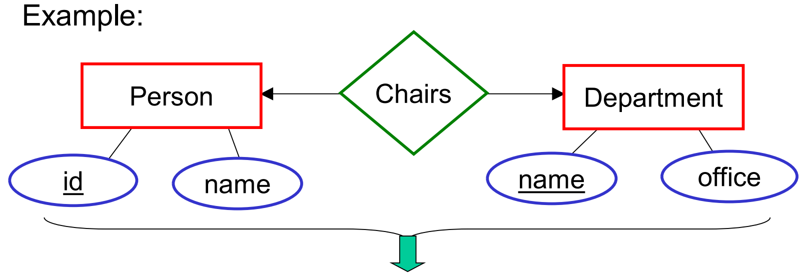
Course

| *name* | *...* | *room_name* |
|---|---|---|
| cscie50b | | Sci Ctr B |
| cscie119 | | Sever 213 |
| cscie160 | | Sci Ctr A |
| cscie268 | | Sci Ctr A |
| cscie160 | | NULL |

- If a large number of entities don't participate in the relationship, it may be better to use a separate relation.

## Special Case: One-to-One Relationship Sets

- Here again, we're able to have only two relations – one for each of the entity sets.
- In this case, we can capture the relationship set in the relation used for *either of the entity sets.*
- Example:




*Person(id, name, chaired_dept)*
*Department(name, office)*

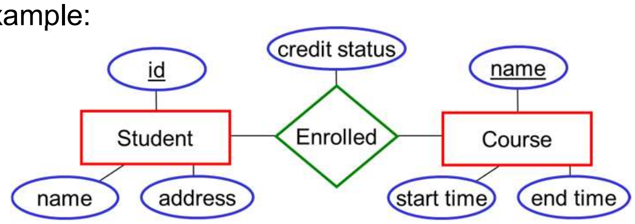
OR

*Person(name, id)*
*Department(name, office, chair_id)*

- which of these would probably make more sense?

## Many-to-Many Relationship Sets

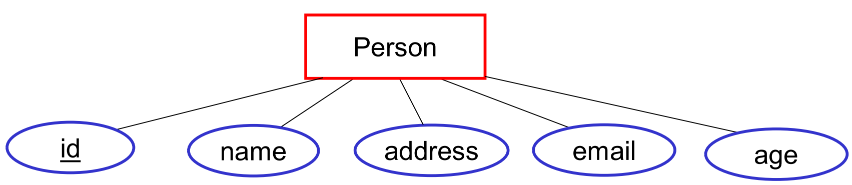
- For many-to-many relationship sets, we need to use a *separate relation* for the relationship set.
  - example:




  - can't capture the relationships in the *Student* table
    - a given student can be enrolled in multiple courses
  - can't capture the relationships in the *Course* table
    - a given course can have multiple students enrolled in it
  - need to use a separate table:
    *Enrolled(student_id, course_name, credit_status)*

## Recall: Primary Key

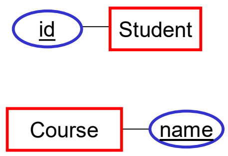
- We typically choose one of the candidate keys as the *primary key.*
- In an ER diagram, we underline the primary key attribute(s).




- In the relational model, we also designate a primary key by underlying it.
  *Person(id, name, address, …)*
- A relational DBMS will ensure that no two rows have the same value / combination of values for the primary key.
  - known as a *uniqueness constraint*

## Primary Keys of Relations for Entity Sets

- When translating an *entity set* to a relation,
  the relation gets the same primary key as the entity set.



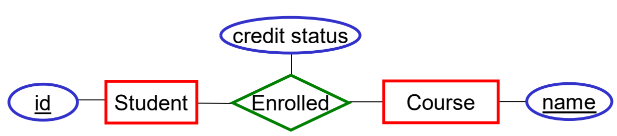

→ *Student(id, …)*

→ *Course(name, …)*

## Primary Keys of Relations for Relationship Sets

- When translating a relationship set to a relation,
  the primary key depends on the cardinality constraints.

- For a *many-to-many* relationship set, we take the union
  of the primary keys of the connected entity sets.




→ *Enrolled(student_id, course_name, credit_status)*

  - doing so prevents a given *combination* of entities
    from appearing more than once in the relation
  - it still allows a single entity (e.g., a single student or course)
    to appear multiple times, as part of different combinations

## Primary Keys of Relations for Relationship Sets (cont.)

- For a *many-to-one* relationship set,
  if we decide to use a separate relation for it,
  what should that relation's primary key include?


→ *Borrows(person_id, isbn)*

## Primary Keys of Relations for Relationship Sets (cont.)

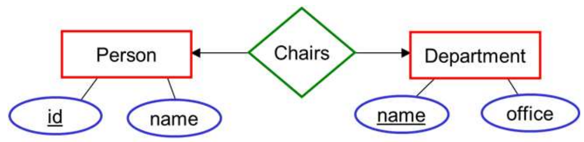
- For a *many-to-one* relationship set,
  if we decide to use a separate relation for it,
  what should that relation's primary key include?


→ *Borrows(person_id, isbn)*

  - limiting the primary key enforces the cardinality constraint
    - in this example, the DBMS will ensure that a given book is borrowed by at most once person
  - how else could we capture this relationship set?

## Primary Keys of Relations for Relationship Sets (cont.)

- For a *one-to-one* relationship set, what should the primary key of the resulting relation be?




→ *Chairs(person_id, department_name)*

## Foreign Keys

- A *foreign key* is attribute(s) in one relation that take on values from the primary-key attribute(s) of another relation.
  - example: *MajorsIn* has <u>two</u> foreign keys

***MajorsIn***

| ***student*** | ***department*** |
|---|---|
| 12345678 | computer science |
| 12345678 | english |
| ... | ... |

*Student*

| ***id*** | ***name*** | ***...*** |
|---|---|---|
| 12345678 | Jill Jones | ... |
| 25252525 | Alan Turing | ... |
| ... | ... | ... |

*Department*

| ***name*** | ***...*** |
|---|---|
| computer science | ... |
| english | ... |
| ... | ... |

- We use foreign keys to capture relationships between entities.
- All values of a foreign key must match the referenced attribute(s) of some tuple in the other relation.
  - known as a *referential integrity* constraint

## Enforcing Constraints

- Example: assume that the tables below show *all* of their tuples.

*MajorsIn*

| ***student*** | ***dept_name*** |
|---|---|
| 12345678 | computer science |
| 12345678 | english |

*Student*

| ***id*** | ***name*** | ***...*** |
|---|---|---|
| 12345678 | Jill Jones | ... |
| 25252525 | Alan Turing | ... |

*Department*

| ***name*** | ***...*** |
|---|---|
| computer science | ... |
| english | ... |

- Which of the following operations would the DBMS allow?
  - adding (12345678, 'John Smith', …) to *Student*
  - adding (33333333, 'Howdy Doody', …) to *Student*
  - adding (12345678, 'physics') to *MajorsIn*
  - adding (25252525, 'english') to *MajorsIn*