Data Management
03 Data Models & Normalization

Matthias Boehm, Patrick Damme

Graz University of Technology, Austria
Computer Science and Biomedical Engineering
Institute of Interactive Systems and Data Science
BMK endowed chair for Data Management

Last update: Mar 18, 2022

Announcements/Org

- **#1 Video Recording**
  - Link in **TeachCenter** & **TUbe** (lectures will be public)
  - Hybrid: HSi13 / https://tugraz.webex.com/meet/m.boehm
- **#2 Exercise 1**
  - Task description published Mar 08 and discussed last week
  - **Deadline: Mar 29, 11.59pm** in TeachCenter

Q&A

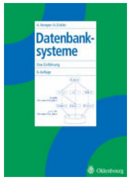
Recap: DB Design Lifecycle Phases

Employee DB

- **#1 Requirements engineering**
  - Collect and analyze data and application requirements
  - → **Specification documents**
- **#2 Conceptual Design** (lecture 02, exercise 1)
  - Model data semantics and structure, independent of logical data model
  - → **ER model / diagram**
- **#3 Logical Design** (lecture 03, exercise 1)
  - Model data with implementation primitives of concrete data model
  - → **e.g., relational schema** + integrity constraints, views, permissions, etc
- **#4 Physical Design** (lecture 07, exercise 2)
  - Model **user-level data organization** in a specific DBMS (and data model)
  - Account for deployment environment and performance requirements

Agenda

- **Relational Data Model**
- **ER-Diagram to Relational Schema**
- **Normalization**



[**Credit:** Alfons Kemper, André Eickler: Datenbanksysteme - Eine Einführung, 10. Auflage. De Gruyter Studium, de Gruyter Oldenbourg 2015, ISBN 978-3-11-044375-2, pp. 1-879]

Relational Data Model

Recap: History 1970/80s (relational)

SQL Standard (SQL-**86**)

↑

SEQUEL

Oracle, IBM DB2, Informix, Sybase → MS SQL

QUEL - - - → **SEQUEL**

Ingres @ UC Berkeley (Stonebraker et al., **Turing Award '14**)

System R @ IBM Research – Almaden (Jim Gray et al., **Turing Award '98**)

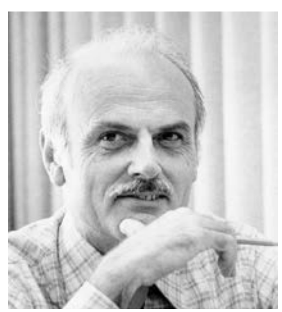
Tuple Calculus

Relational Algebra

Relational Model

Goal: **Data Independence** (physical data independence)

- Ordering Dependence
- Indexing Dependence
- Access Path Depend.



Edgar F. "Ted" Codd @ IBM Research (**Turing Award '81**)

Recommended Reading

[E. F. Codd: A Relational Model of Data for Large Shared Data Banks. Comm. ACM 13(6), **1970**]

Relations and Terminology

- **Domain D (value domain): e.g., Set S, INT, Char[20]**
- **Relation R**
  - **Relation schema** RS:
    Set of k attributes $\{A_1,\ldots,A_k\}$
  - **Attribute** A_j: value domain D_j = dom(A_j)
  - **Relation:** subset of the Cartesian product over all value domains D_j
    $\mathbf{R \subseteq D_1 \times D_2 \times \ldots \times D_k,\ k \geq 1}$

Attribute

A1 INT	A2 INT	A3 BOOL
3	7	T
1	2	T
3	4	F
1	7	T

Tuple

cardinality: 4
rank: 3

- **Additional Terminology**
  - **Tuple**: row of k elements of a relation
  - **Cardinality** of a relation: number of tuples in the relation
  - **Rank** of a relation: number of attributes
  - **Semantics:** **Set** := no duplicate tuples (in practice: **Bag** := duplicates allowed)
  - **Order of tuples and attributes is irrelevant**

Relations and Terminology, cont.

- **Database Schema**
  - Set of relation (table) schemas and constraints
- **Database**
  - Set of actual relations, including data
  - Database instance: current status of database
- **NULL**
  - Special **NULL** value for unknown or missing values
  - Part of every domain, unless **NOT NULL constraint** specified
  - Special semantics for specific operations, e.g., three-value Boolean logic

```
TRUE OR NULL → TRUE
FALSE OR NULL → NULL
TRUE AND NULL → NULL
FALSE AND NULL → FALSE
```

Comparisons

~~WHERE X = NULL~~ → NULL

WHERE X IS NULL

Example UniversityDB

- **Professors**

PID	Title	Firstname	Lastname
1	Univ.-Prof. Dipl.-Inf. Dr.	Stefanie	Lindstaedt
3	Assoc.Prof. Dipl.-Ing. Dr.techn.	Viktoria	Pammer-Schindler
7	Univ.-Prof. Dr.-Ing.	Matthias	Boehm

- **Courses**

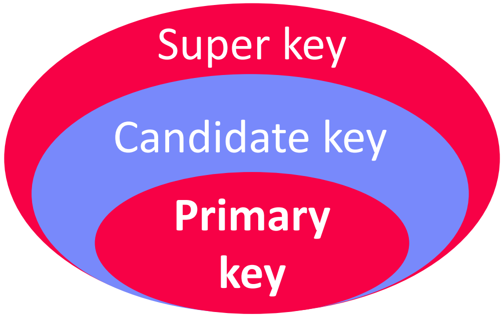
	CID	Title	ECTS
Summer/ Winter	INF.01017UF	Data Management (VO)	3
	INF.02018UF	Data Management (KU)	1
	706.010	Databases	3
Winter	706.520	Data Integration and Large-Scale Analysis	5
	706.543	Architecture of Database Systems	5
Summer	706.550	Architecture of Machine Learning Systems	5

Primary and Foreign Keys

- **Primary Key X**
  - **Minimal set of attributes** X that **uniquely identifies tuples** in a relation R
  - E.g., PID=1 ➔

1	Univ.-Prof. Dipl.-Inf. Dr.	Stefanie	Lindstaedt

  - **#1 Unique:** $\forall t_i, t_j \in R: t_i[X] = t_j[X] \Rightarrow i = j$
  - **#2 Defined:** $\forall t_i \in R: t_i[X] \neq NULL$
  - **#3 Minimal:** no attribute can be removed wrt #1
  - Super key: #1-2, **candidate key:** #1-3, **primary key:** pick one of the candidate keys



- **Foreign Key**
  - Reference of a primary key in another relation

1 **Professors**

<u>PID</u>	Title	First Name	Last Name

N **Courses**

<u>CID</u>	Title	ECTS	PID

Primary and Foreign Keys, cont.

- **Example Airports**
  - Airport Name
  - **IATA** (International Air Transport Association) code
  - **ICAO** (International Civil Aviation Organization) code
  - Latitude
  - Longitude
  - Altitude

Graz Airport
GRZ
LOWG
46.9911
15.4396
1115 [ft]

- **Q: Candidate Keys**
  - Natural candidate keys: **IATA**, **ICAO**
  - [Surrogate (artificial) candidate key]
- **Q: Primary Keys**
  - IATA **or** ICAO, **or**
  - [Surrogate key]

Preview Next Lectures

- **Relational Algebra [Lecture 04]**
  - **Operands: relations** (variables for computing new values)
  - **Operators**: traditional set operations and specific relational operations (symbols representing the computation)

- **Structured Query Language (SQL) [Lecture 05]**
  - **Data Definition Language (DDL)** → Manipulate the database schema
  - Data Manipulation Language (DML) → Update and query database

Example CREATE TABLE

```
CREATE TABLE Professors (
   PID INTEGER PRIMARY KEY,
   Title VARCHAR(128),
   Firstname VARCHAR(128),
   Lastname VARCHAR(128)
);
```

```
CREATE TABLE Courses (
   CID INTEGER PRIMARY KEY,
   Title VARCHAR(256),
   ECTS INTEGER NOT NULL,
   PID INTEGER
      REFERENCES Professors
);
```

Alternative for composite primary key:

```
CREATE TABLE R (
   ...,
   PRIMARY KEY(A1, A2)
);
```

Alternative for composite foreign key:

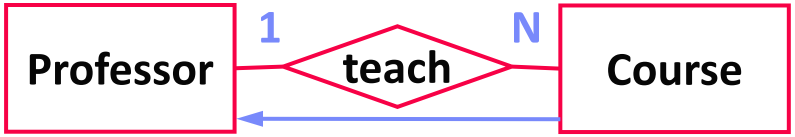
```
CREATE TABLE S (
   ...,
   FOREIGN KEY(A1, A2)
      REFERENCES R(A1, A2)
);
```

Referential Integrity Constraints

- **Foreign Keys:**
  - Reference of a primary key in another relation
  - **Referential integrity:** FK need to reference existing tuples or NULL

- **Enforcing Referential Integrity**
  - **#1 Error** (default)

```
DELETE FROM Professors WHERE PID=7
```



  - **#2 Propagation** on request
    - E.g., for existential dependence

```
CREATE TABLE Courses (...
   PID INTEGER REFERENCES Professors
      ON DELETE CASCADE);
```

  - **#2 Set NULL** on request
    - E.g., for independent entities

```
CREATE TABLE Courses (...
   PID INTEGER REFERENCES Professors
      ON DELETE SET NULL);
```

Domain and Semantic Constraints

- **Domain/Semantic Constraints**
  - Value constraints of individual attributes (single and multi-column constraints)
  - **CHECK:** Value ranges or enumerated valid values
  - Explicit naming via **CONSTRAINT**

```
CREATE TABLE Courses (
   CID INTEGER PRIMARY KEY,
   ECTS INTEGER
      CHECK (ECTS BETWEEN 1 AND 10)
);
```

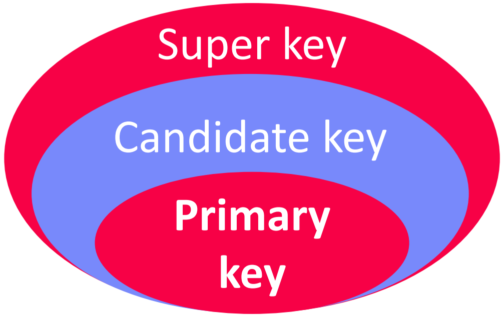
(**In ProstgreSQL:** no subqueries in CHECK constraints)

- **UNIQUE Constraints**
  - Enforce uniqueness of non-primary key attribute
- **NOT NULL Constraints**
  - Enforce known / existing values, potentially with DEFAULT
- **Triggers** (in lecture 05)
  - Run stored procedures on insert/delete/update
  - Full flexibility to specify arbitrary complex constraints

BREAK (and Test Yourself), cont.

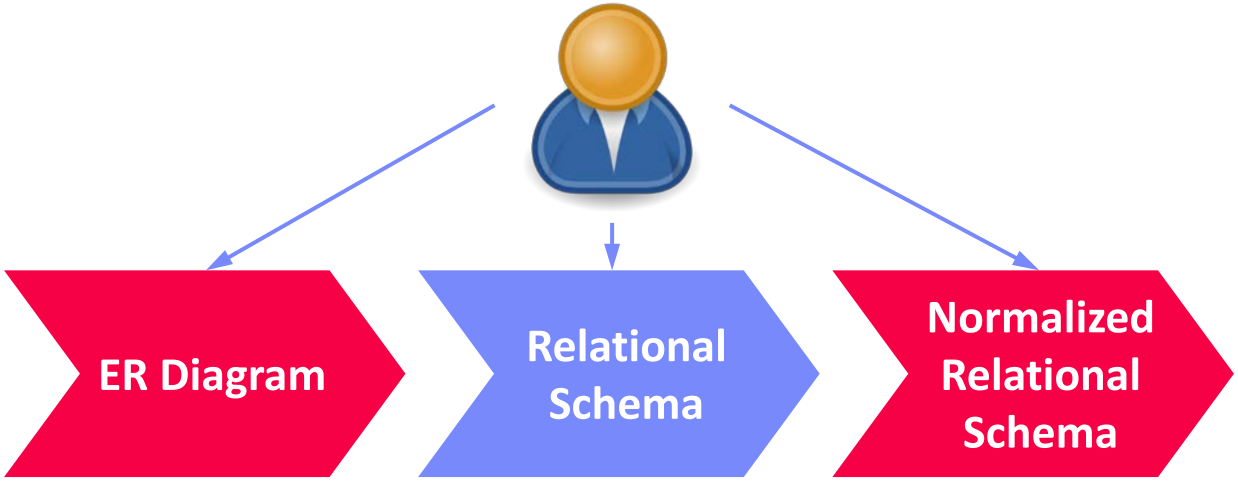
- **Task: Assume Student(SID, Name, DoB), where SID is unique and defined (not null). List valid super and candidate keys** (2/100 points)

- **Super Keys**
  - (SID)
  - (SID, Name)
  - (SID, DoB)
  - (SID, Name, DoB)

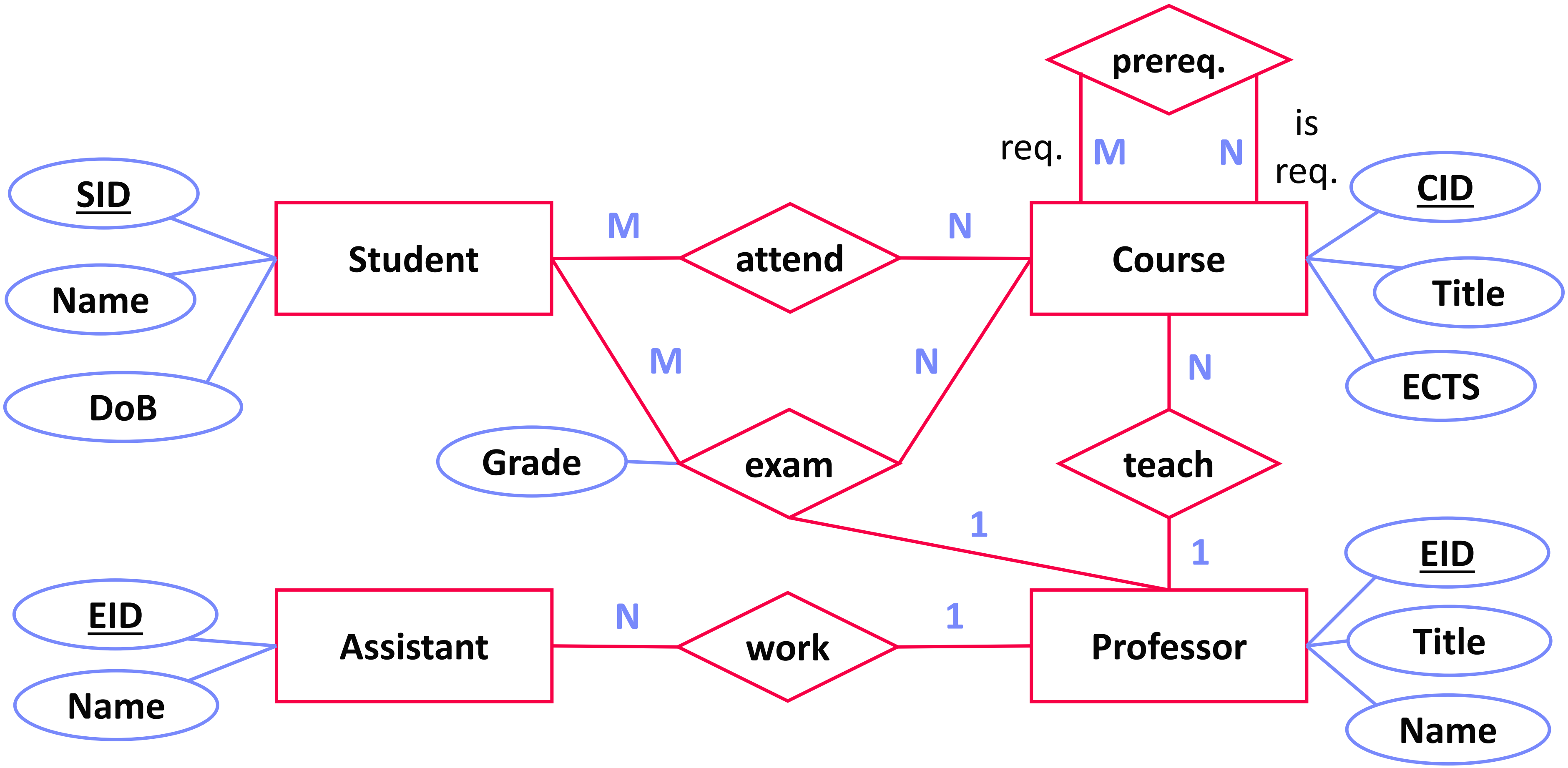


- **Candidate Keys**
  - (SID)

ER-Diagram to Relational Schema



Recap: UniversityDB



Step 1: Mapping Entity Types

- **Each entity type directly maps to a relation**
  - Introduce surrogate (artificial) keys if needed
- **Examples**

Student

```
Students(
  SID:INTEGER, Name:VARCHAR(128), DoB:DATE)
```

Course

```
Course(
  CID:INTEGER, Title:VARCHAR(256), ECTS:INTEGER)
```

Professor

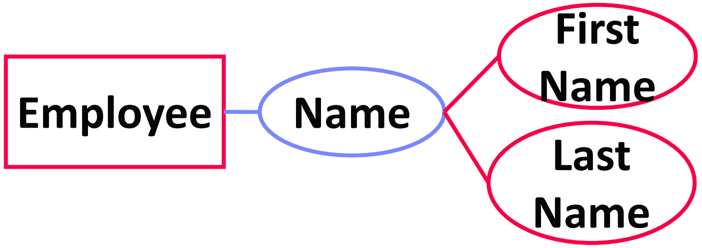
```
Professor(
  EID:INTEGER, Title:VARCHAR(128), Name:VARCHAR(256))
```

Assistant

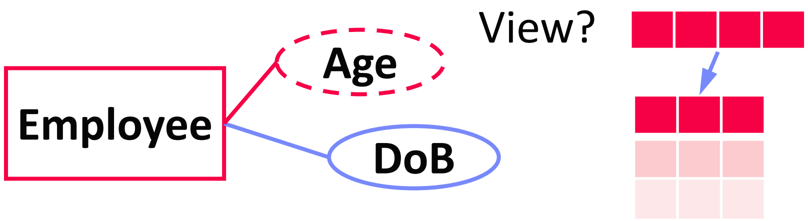
```
Assistant(
  EID:INTEGER, Name:VARCHAR(256))
```

Step 2: Mapping Attributes

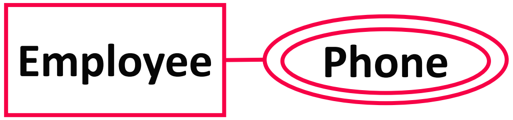
- **Atomic Attributes**
  - Direct mapping to attributes of relation
  - Choice of **data types and constraints**
- **Composite Attributes**
  - **Split into atomic attributes**,
  - Composite value, or
  - Object-relational data types



- **Derived Attributes**
  - Generated columns or **via views**

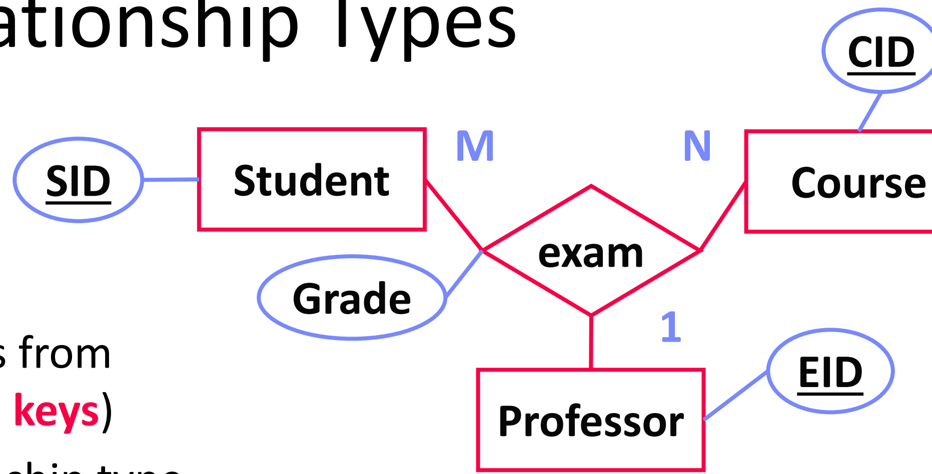


- **Multi-valued Attributes**
  - **Relation with FK** to originating relation



Step 3: Mapping Relationship Types

- **Generic Solution**
  - Map every relationship type to a **relation**
  - **Compose primary key** of keys from involved entity types (**foreign keys**)
  - **Append attributes** of relationship type
  - **Recursive relationships:** careful naming



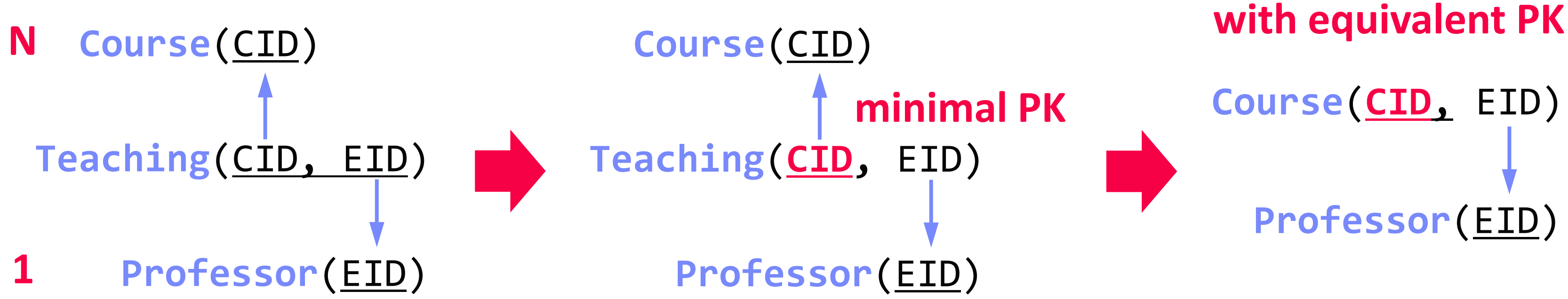
Exams (foreign keys: {SID}, {CID}, {EID}; primary key: {SID, CID, EID})

SID[FK]	CID[FK]	EID[FK]	Grade
12345	706.010	7	1.0
12399	706.550	7	1.7
12399	706.010	7	1.3
12282	INF.01017UF	7	1.0

Step 4: Simplification

- **Issue: Unnecessary Relation per Relationship Type**
  ➔ Simplify 1:1, 1:N, N:1 relationship types

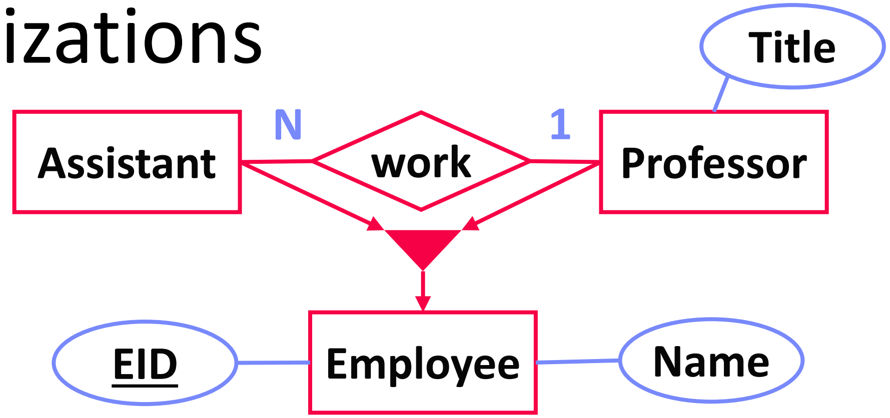
Merge relations with equivalent PK



- **Examples Fused Step 3-4**
  - For **E1 – R – E2**
  - Modified Chen

Cardinality	Implementation
1:1	One relation **E12**, PK from E1 or E2
C:1	One relation **E12** (or two), PK from **E2**
1:M	Two relations **E1** + **E2**, E2 w/ FK to E1 (see Professor-Course above)
MC:MC	Three relations **E1**, **R**, **E2**; R w/ FKs to E1/E2

Step 5: Mapping Specializations



- **#1 Universal Relation**
  - One relation, **NULL** assigned for non-applicable attributes
  - ➔ **Employee**

- **#2 Object-oriented**
  - One relation per specialized entity
  - Horizontally partitioned
  - ➔ **Employee, Assistant, Professor**

EID	Name

EID	Title	Name
7	Univ.-Prof. Dr.-Ing.	Matthias Boehm

- **#3 ER-oriented**
  - One relation per specialized entity
  - Vertically partitioned
  - ➔ **Employee, Assistant, Professor**

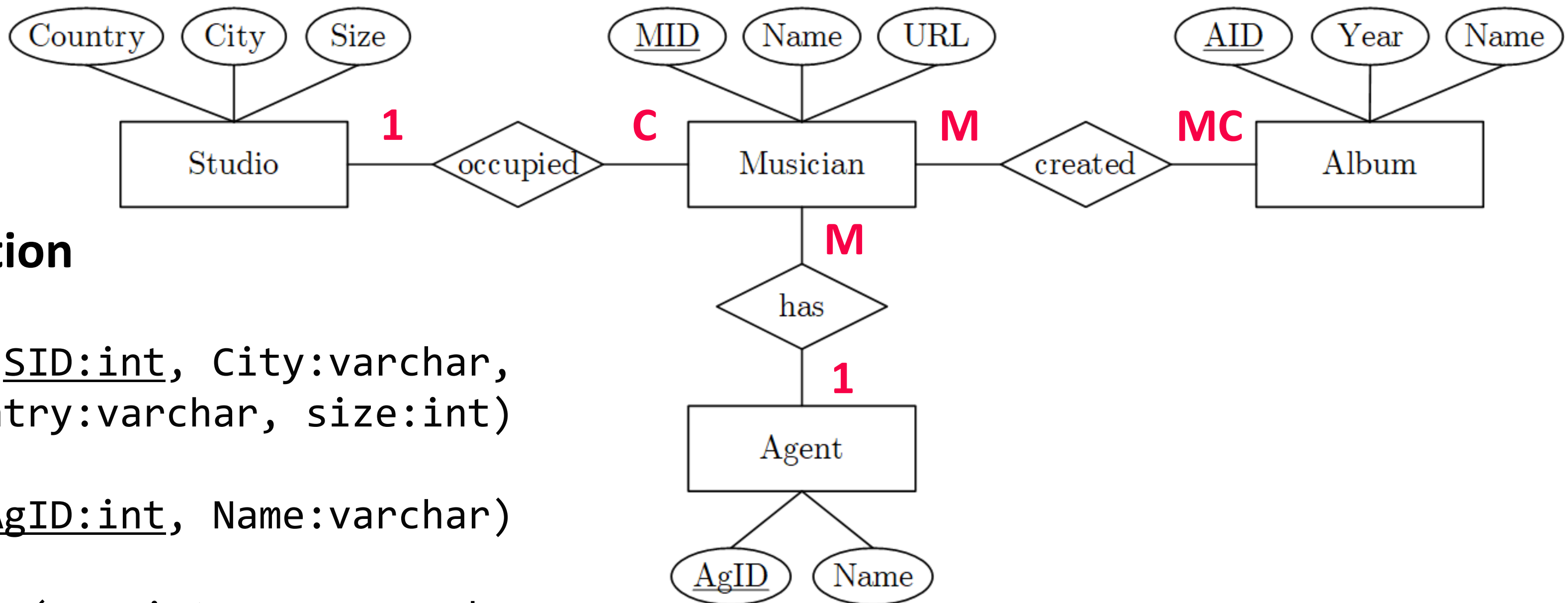
EID	Name
7	Matthias Boehm

EID	Title
7	Univ.-Prof. Dr.-Ing.

[Jeffrey D. Ullman: CS145 Introduction to Databases - Entity-Relationship Model, Stanford **2007**]

BREAK (and Test Yourself)

- **Task: Map the given ER diagram into a relational schema, including data types, primary keys, and foreign keys** (9/100 points)



- **Solution**

Studio(SID:int, City:varchar, Country:varchar, size:int)

Agent(AgID:int, Name:varchar)

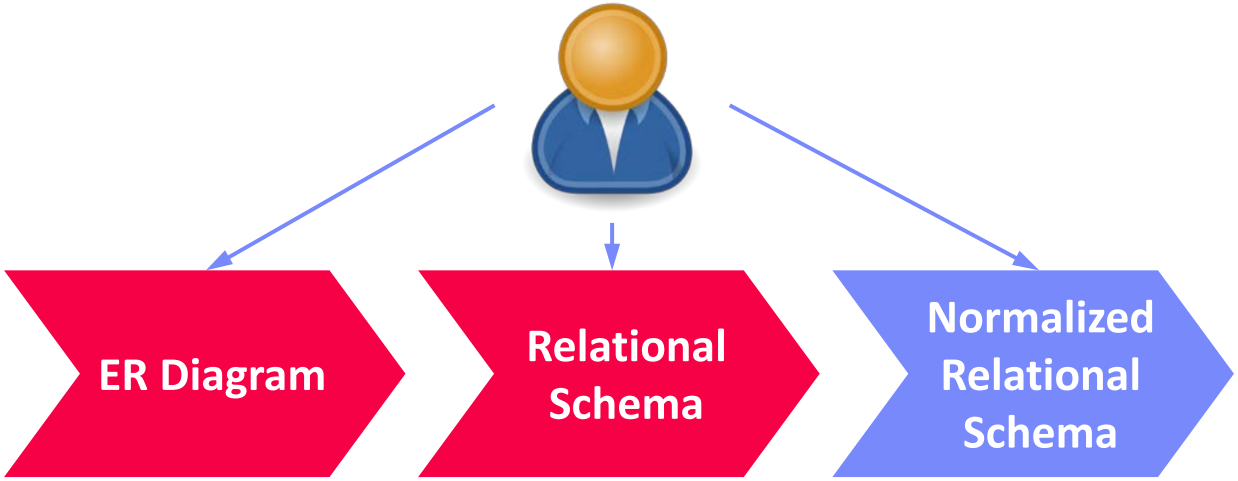
Musician(MID:int, Name:varchar, URL:varchar, SID^{FK}:int, AgID^{FK}:int)

Album(AID:int, Year:int, Name:varchar)

Created(MID^{FK}:int, AID^{FK}:int)

5x relations
1x data types
1x primary keys
1x FKs in Musician
1x Composite PK in Created

Normalization



Motivation Poor Relational Schemas

ProfCourse (mixed entity types → **redundancy**)

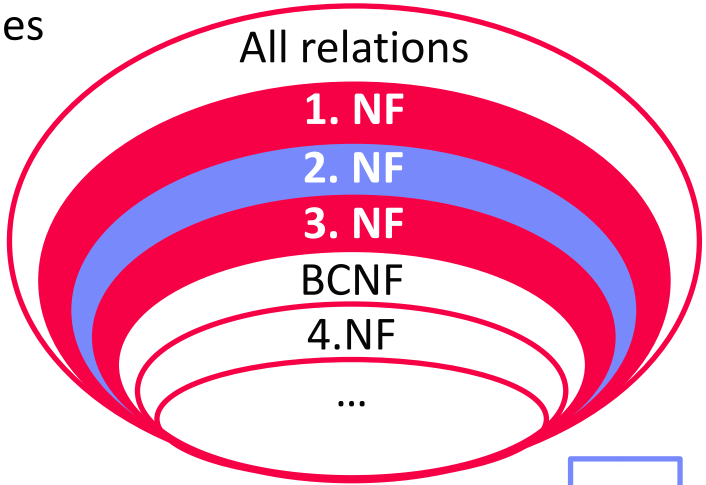
EID	Name	CID	Title	ECTS
7	Boehm	INF.01014UF	Data Management (VO)	3
7	Boehm	INF.02018UF	Data Management (KU)	1
7	Boehm	706.010	Databases	3
7	Boehm	706.520	Data Integration and Large-Scale Analysis	5
7	Boehm	706.543	Architecture of Database Systems	5
7	Boehm	706.550	Architecture of Machine Learning Systems	5

- **Insert Anomaly:** How to insert a new lecture or prof?
- **Update Anomaly:** How to update "Boehm" → "Böhm"?
- **Delete Anomaly:** What if we delete all data management lectures?

→ Normalization: **Find good schema to avoid redundancy, ensure consistency, and prevent information loss**

Overview Normalization

- **Normalization Process**
  - "[…] **reversible process** of replacing a given collection of relations […] a progressively **simpler and more regular structure**"
  - Principled approach of **improving the quality** (redundancy, inconsistencies)
  - Input: DB-Schema and functional dependencies



- **1st Normal Form: no multi-valued attributes**
- **2nd Normal Form: all non-key attributes fully functional dependent on primary key**
- **3rd Normal Form: no dependencies among non-key attributes**
- Boyce-Codd Normal Form (BCNF)
- 4th, 5th,6th Normal Form

[E. F. Codd: Normalized Data Structure: A Brief Tutorial. SIGFIDET Workshop 1971]

[E. F. Codd: Further Normalization of the Data Base Relational Model. IBM Research Report, San Jose, California RJ909 (1971)]

Unnormalized Relation

- **Relation PartProject**

P#	PDesc	Qty	Project (J#, JDesc, Mgr, Qty)			
203	CAM	30	12	Sorter	007	5
			73	Collator	086	7
206	COG	155	12	Sorter	007	33
			29	Punch	086	25
			36	Reader	111	16

- **Issues**
  - Column **'Project'** is **not atomic, but set of tuples**
  - **Redundancy** across projects appearing in multiple parts

- **Solution:**
  - Create multiple tables with PK-FK relationships

1st Normal Form

- **Definition and Approach**
  - Relation is in 1NF if all its **attributes are atomic**
  - ➔ **Split relations with 1:N and M:N relationships (lossless)**

- **Example**

Relation Part

P#	PDesc	Qty
203	CAM	30
206	COG	155

Relation Project

FK

P#	J#	JDesc	Mgr	Qty
203	12	Sorter	007	5
203	73	Collator	086	7
206	12	Sorter	007	33
206	29	Punch	086	25
206	36	Reader	111	16

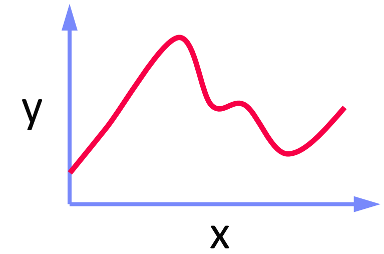
JDesc, Mgr: depend on J#

Qty: depends on (J#,P#)

- **Issues**
  - **Insert anomaly** (e.g., no project without parts)
  - **Update anomaly** (e.g., redundant updated Mgr)
  - **Delete anomaly** (e.g., project deleted on last part)

Background: Functional Dependency

- **Function y = f(x)**
  - For deterministic functions f, the value x determines y (aka, y depends on x)

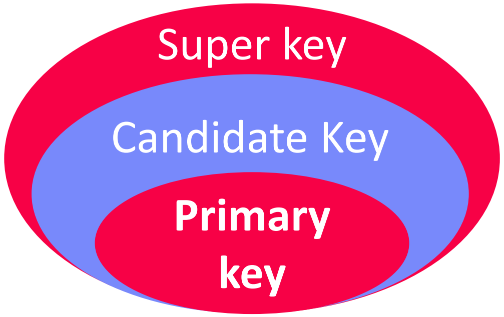


- **Functional Dependency (FD) X → Y**
  - X and Y are sets of attributes, Y functionally depends on X
  - $X \rightarrow Y \;\Leftrightarrow\; \forall\, t_1, t_2 \;\in R: t_1[X] = t_2[X] \Rightarrow t_1[Y] = t_2[Y]$
- **Examples**
  - J# → {JDesc,Mgr}
  - {P#,J#} → Qty
- **FDs derived from schema semantics not existing data**

P#	J#	JDesc	Mgr	Qty
203	12	Sorter	007	5
203	73	Collator	086	7
206	12	Sorter	007	33
206	29	Punch	086	25
206	36	Reader	111	16

Background: Functional Dependency, cont.

- **Full Functional Dependency**
  - Full functional dependency X → Y iff there is no proper subset $Z \subset X$ such that Z → Y
  - **Candidate key:** X → relational schema (**minimal**)



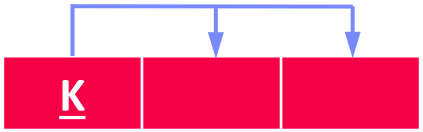
- **Implied FDs via Armstrong Axioms**
  - Given a set **F** of FDs, the **closure F+** is the set of all implied FDs (which can be derived by the following axioms)
  - Reflexivity: $X \supseteq Y \Rightarrow X \rightarrow Y$
  - Augmentation: $X \rightarrow Y \Rightarrow XZ \rightarrow YZ$
  - Transitivity: $(X \rightarrow Y) \wedge (Y \rightarrow Z) \Rightarrow X \rightarrow Z$

- **Composition**
  - Composition: $(X \rightarrow Y) \wedge (X \rightarrow Z) \Rightarrow X \rightarrow YZ$
  - Decomposition: $X \rightarrow YZ \Rightarrow (X \rightarrow Y) \wedge (X \rightarrow Z)$
  - Pseudo-Transitivity: $(X \rightarrow Y) \wedge (YW \rightarrow Z) \Rightarrow XW \rightarrow Z$

Example:
(J# → JDesc, J# → Mgr)
➔ (J# → {JDesc,Mgr})

2nd Normal Form

- **Definition and Approach**
  - Relation is in 2NF if it's **in 1NF** and every non-key attribute **fully functional dependent** from every candidate key



  → **Split relations with 1:N and M:N relationships (lossless)**

- **Example**

Relation Part

P#	PDesc	Qty
203	CAM	30
206	COG	155

Relation PJ

FK FK

P#	J#	Qty
203	12	5
203	73	7
206	12	33
206	29	25
206	36	16

Relation Project

J#	JDesc	Mgr
12	Sorter	007
73	Collator	086
29	Punch	086
36	Reader	111

Split PJ and Project because J# → {JDesc, Mgr}, **instead of {P#,J#} → {JDesc, Mgr}**

3rd Normal Form

- **Definition and Approach**
  - Relation is in 3NF if it's **in 2NF** and every non-key attribute is **non-transitively dependent** from every candidate key (→ no non-key dependencies)
  - → **Split relations with 1:N and M:N relationships (lossless)**
  - Preserves all dependencies but might still contain anomalies (→ BCNF)

- **Example**
  NOT in 3NF
  - **E# → D#**
  - **D#→DMgr**
  - **D#→CType**

Relation Employee

E#	JCode	D#	DMgr	CType
1	A	X	11	G
2	C	X	11	G
3	A	Y	12	N
4	B	X	11	G
5	B	Y	12	N
6	C	Y	12	N
7	A	Z	13	N
8	C	Z	13	N

3rd Normal Form, cont.

- **Example**

Relation Employee FK (D#)

E#	JCode	D#
1	A	X
2	C	X
3	A	Y
4	B	X
5	B	Y
6	C	Y
7	A	Z
8	C	Z

Relation Department

D#	DMgr	CType
X	11	G
Y	12	N
Z	13	N

→ **"Denormalization":**
Conscious creation of materialized views in non-3NF/2NF to improve performance (primarily for read-only DBs)

BREAK (and Test Yourself #2)

- **Task: Assume the functional dependency City→Country. Bring your schema into 3NF and explain why it is in 3NF** (prev. exam 10/100 points)

```
Studio(SID:int, City:varchar, Country:varchar, size:int)
```

- **Solution**

```
Studio(SID:int, CName^FK:varchar, size:int)

Cities(CName:varchar, Country:varchar)
```

  - **1st Normal Form:** no multi-valued attributes
  - **2nd Normal Form:** all non-key attributes fully functional dependent on PK
  - **3rd Normal Form:** no dependencies among non-key attributes

Conclusions and Q&A

- **Summary**
  - Fundamentals of the relational data model + SQL DDL
  - Mapping ER diagrams into relational schemas
  - Relational normalization (1NF, 2NF, 3NF)
- **Exercise 1 Reminder**
  - All background to solve tasks 1.1 and 1.2 (25/25)
  - **Deadline: Mar 29, 11.59pm** in TeachCenter, **draft submissions** are fine
  - Make use of the news group and office hours
- **Next lectures**
  - **04 Relational Algebra and Tuple Calculus** [Mar 28]
  - **05 Query Languages (SQL, XML, JSON)** [Apr 04]
  - **Easter break** (lecture continuing Apr 25)