B0B36DBS, BD6B36DBS: **Database Systems**

http://www.ksi.mff.cuni.cz/~svoboda/courses/172-B0B36DBS/

Lecture 2

Relational Model

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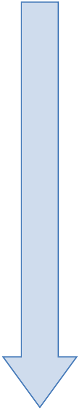
Lecture Outline

- **Logical database models**
  - Basic overview
- Model-Driven Development
- **Relational model**
  - Description and features
  - **Transformation of ER / UML conceptual schemas**

Logical Database Models

Layers of Database Modeling

Abstraction



Implementation

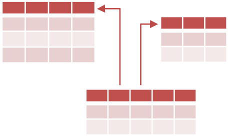
- **Conceptual layer**
  - Models a part of the structured real world relevant for applications built on top of our database
- **Logical layer**
  - Specifies how conceptual components (i.e. **entity types, relationship types, and their characteristics**) are represented in **logical data structures** that are interpretable by machines
- **Physical layer**
  - Specifies how logical database structures are implemented in a specific technical environment

Logical Layer

- **What are these logical structures?**
  - Formally…
    - **Sets, relations, functions, graphs, trees, …**
      - I.e. traditional and well-defined mathematical structures
  - Or in a more friendly way…
    - **Tables**, rows, columns, …
    - **Objects**, pointers, …
    - **Collections**, …
    - …

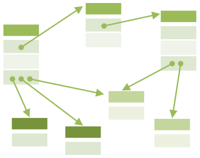
Logical Models

- Models based on **tables**
  - Structure
    - **Rows** for entities
    - **Columns** for attributes
  - Operations
    - **Selection**, **projection**, **join**, …
  - Examples
    - **Relational model**
    - … and various derived **table models** introduced by:
      - **SQL** (as it is standardized)
      - and particular implementations like Oracle, MySQL, …



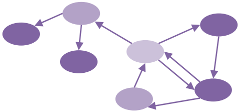
Logical Models

- Models based on **objects**
  - Structure
    - **Objects** with **attributes**
    - **Pointers** between objects
  - Motivation
    - Object-oriented programming (OOP)
    - Encapsulation, inheritance, …
  - Operations
    - **Navigation**



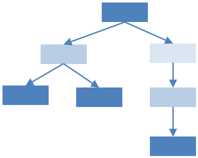
Logical Models

- Models based on **graphs**
  - Structure
    - Vertices, edges, attributes
  - Operations
    - **Traversals, pattern matching, graph algorithms**
  - Examples
    - Network model (one of the very first database models)
    - **Resource Description Framework** (RDF)
    - **Neo4j**, InfiniteGraph, OrientDB, FlockDB, …



Logical Models

- Models based on **trees**
  - Structure
    - **Vertices** with attributes
    - **Edges** between vertices
  - Motivation
    - Hierarchies, categorization, semi-structured data
  - Examples
    - Hierarchical model (one of the very first database models)
    - **XML** documents
    - **JSON** documents

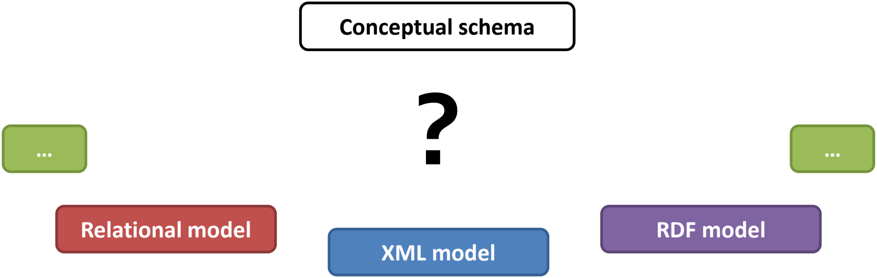


Overview of Logical Models

- **There are plenty of** (different / similar) **models**
    - *The previous overview was intended just as an insight into some of the basic ideas and models*
  - Hierarchical, network, **relational**, **object**, **object-relational**, **XML**, **key-value**, **document-oriented**, **graph**, ...
- Why so many of them?
  - **Different models are suitable in different situations**
  - Not everything is (yet) standardized, proprietary approaches or extensions often exist

Logical Modeling

- Step 1: **Selection of the right logical model**



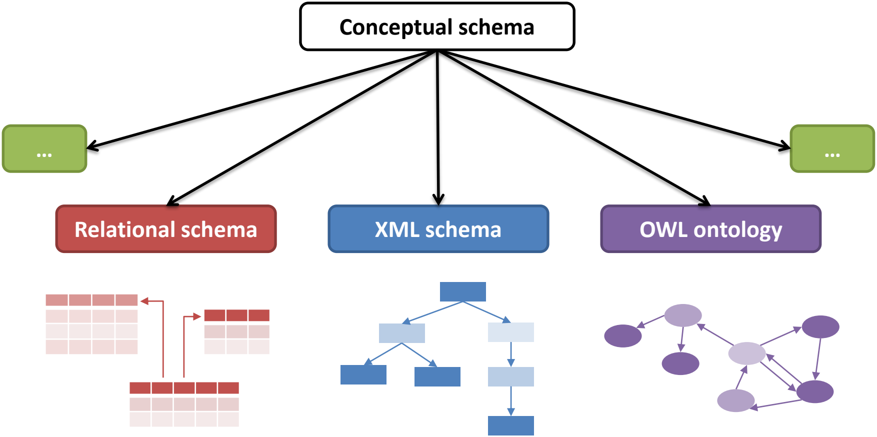
- Note that…
  - **Relational model is not always the best solution**

Logical Modeling

- Step 1: **Selection of the right logical model**
  - According to…
    - **Data characteristics**
      - True nature of real-world entities and their relationships
    - **Query possibilities**
      - Available access patterns, expressive power, …
    - **Intended usage**
      - Storage (JSON data in document-oriented databases, …)
      - Exchange (XML documents sent by Web Service, …)
      - Publication (RDF triples forming the Web of Data, …)
      - …
    - **Identified requirements**

Logical Modeling

- Step 2: **Creation of a logical schema**



Logical Modeling

- Step 2: **Creation of a logical schema**
  - Goal
    - **Transformation of a conceptual schema** to a logical one
  - Real-world applications often need **multiple schemas**
    - Focus on different parts of the real world
    - Serve different components of the system
    - **Even expressed in different logical models**
  - Challenge: **can this be achieved automatically?**
      - Or at least semi-automatically?
    - Answer: **Model-Driven Development**

Model-Driven Development (MDD)

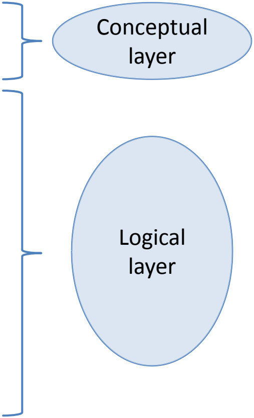
Model-Driven Development

- **MDD**
  - Software development approach
    - **Executable schemas instead of executable code**
      - I.e. schemas that can be automatically (or at least semi-automatically) converted to executable code
    - **Unfortunately, just in theory**… recent ideas, **not yet fully applicable in practice today** (lack of suitable tools)

- MDD principles can be used for **database modeling** as well

Terminology

- Levels of abstraction
  - **Platform-Independent Level**
    - Hides particular platform-specific details
  - **Platform-Specific Level**
    - Maps the conceptual schema (or its part) to a given logical model
    - Adds platform-specific details
  - **Code Level**
    - Expresses the schema in a selected machine-interpretable logical language
    - SQL, XML Schema, OWL, …

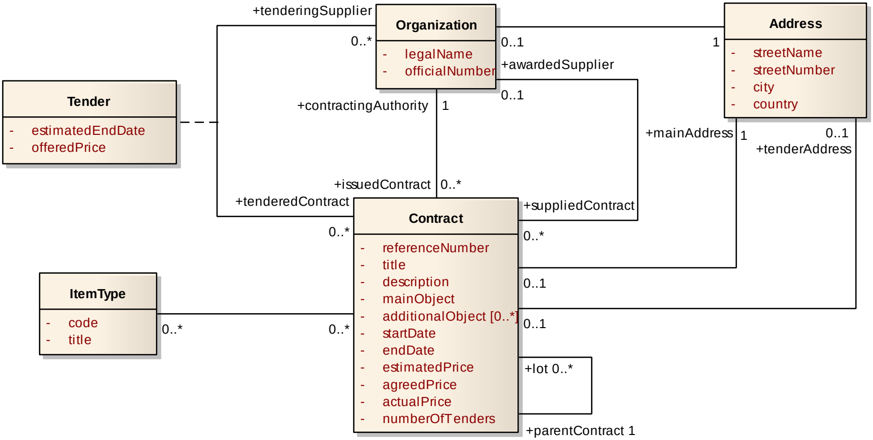


Real-World Example

- Information System for Public Procurement
  - http://www.isvzus.cz/
  - There are several logical models used:
    - **Relational data model**
      - for data storage
    - **XML data model**
      - for exchanging data with information systems of public authorities which issue public contracts
    - **RDF data model**
      - for publishing data on the Web of Linked Data in a machine-readable form (at least this is a goal…)

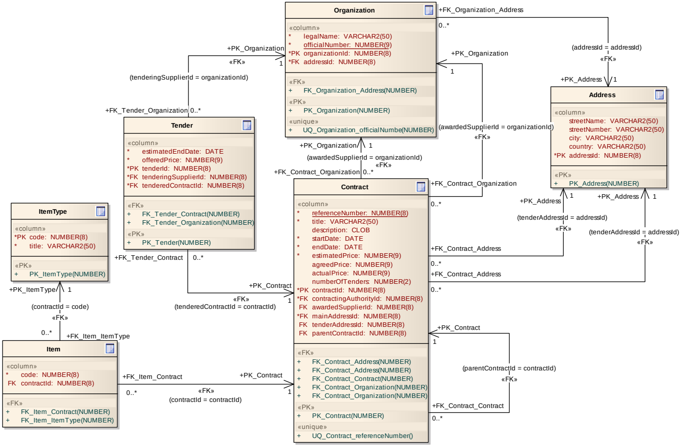
Real-World Example

- Platform-independent schema



Real-World Example

- Platform-specific schema: **relational model**



Real-World Example

- Platform-specific schema: **relational model**
  - Notes to the previous UML diagram
    - It is a UML class diagram
      - But enhanced with features for modeling logical schemas in (object-)relational model
    - **Stereotypes** allow us to add **specific semantics** to basic constructs (class, attribute, association), e.g.,
      - <<table>> specifies that a class represents a table
      - <<PK>> specifies that an attribute models a primary key
      - <<FK>> specifies that an attribute/association models a foreign key
      - etc.

Real-World Example

- Code level: **SQL** (snippet)

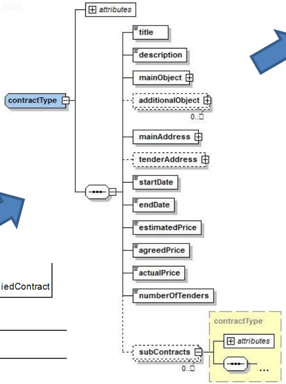
```
CREATE TABLE Contract (
  referenceNumber NUMBER(8) NOT NULL,
  title VARCHAR2(50) NOT NULL,
  description CLOB,
  startDate DATE NOT NULL,
  endDate DATE NOT NULL,
  estimatedPrice NUMBER(9) NOT NULL,
  ...
);

ALTER TABLE Contract ADD CONSTRAINT PK_Contract
  PRIMARY KEY (contractId);
ALTER TABLE Contract ADD CONSTRAINT FK_Contract_Address
  FOREIGN KEY (mainAddressId) REFERENCES Address (addressId);
...

CREATE TABLE Organization(...);
...
```

Real-World Example

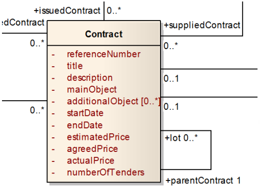
- Code level: **SQL** (snippet)
  - The previous code was generated **fully automatically**
    - from a platform-specific diagram
      - **It has to contain all the necessary information**
    - using a **CASE tool** (Computer-Aided Software Engineering)
      - Which can detect errors and
      - helps with the specification

Real-World Example

- **XML**



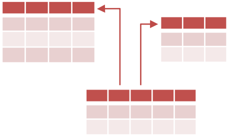

```
<?xml version="1.0" encoding="UTF-8"?>
<!-- edited with XMLSpy v2012 sp1 (http://www.altova.com) by IM (Charles
<xs:schema xmlns:xs="http://www.w3.org/2001/XMLSchema">
	<xs:complexType name="addressType">
		<xs:sequence>
			<xs:element name="streetName"/>
			<xs:element name="streetNumber"/>
			<xs:element name="city"/>
			<xs:element name="country"/>
		</xs:sequence>
	</xs:complexType>
	<xs:complexType name="objectType">
		<xs:sequence>
			<xs:element name="code" type="xs:int"/>
			<xs:element name="title" type="xs:string"/>
		</xs:sequence>
	</xs:complexType>
	<xs:complexType name="contractType">
		<xs:sequence>
			<xs:element name="title" type="xs:string"/>
			<xs:element name="description" type="xs:string"/>
			<xs:element name="mainObject" type="objectType"/>
			<xs:element name="additionalObject" type="objectT
			<xs:element name="mainAddress" type="addressType"
			<xs:element name="tenderAddress" type="addressTyp
			<xs:element name="startDate" type="xs:date"/>
			<xs:element name="endDate" type="xs:date"/>
			<xs:element name="estimatedPrice" type="xs:float"
			<xs:element name="agreedPrice" type="xs:float"/>
			<xs:element name="actualPrice" type="xs:float"/>
			<xs:element name="numberOfTenders" type="xs:int"/
			<xs:element name="subContracts" type="contractTyp
		</xs:sequence>
		<xs:attribute name="referenceNumber" type="xs:int"/>
	</xs:complexType>
	<xs:complexType name="tenderedContractType">
```



Relational Model

Relational Model

- **Relational model**
  - Allows to store entities, relationships, and their attributes in **relations**
  - Founded by E. F. Codd in 1970



- Informally…
  - **Table** = collection of **rows**, each row represents one entity, values of **attributes** are stored in **columns**
  - Tables are more intuitive,
    but conceal important mathematical background

Relational Model

- Definitions and terminology
  - **Schema of a relation**
    - Description of a relational structure (everything except data)
    - $S(A_1:T_1,\ A_2:T_2,\ \ldots,\ A_n:T_n)$
      - S is a schema name
      - A_i are attribute names and T_i their types (attribute domains)
      - Specification of types is often omitted
    - Example:
      - `Person(personalId, firstName, lastName)`
  - **Schema of a relational database**
    - Set of relation schemas (+ integrity constraints, …)

Relational Model

- Definitions and terminology for **data**
  - **Relation**
    - Subset of the Cartesian product of attribute domains T_i
      - I.e. **relation is a set**
    - Items are called **tuples**
  - **Relational database**
    - Set of relations

Relational Model

- Basic requirements (or consequences?)
  - **Atomicity** of attributes
    - Only simple types can be used for domains of attributes
  - **Uniqueness** of tuples
    - Relation is a set, and so **two identical tuples cannot exist**
  - **Undefined order**
    - Relation is a set, and so **tuples are not mutually ordered**
  - **Completeness** of values
    - There are no *holes* in tuples, i.e. **all values are specified**
      - However, special `NULL` values (well-known from relational databases) can be added to attribute domains

Integrity Constraints

- **Identification**
  - – Every tuple is identified by one or more attributes
  - **Superkey** = set of such attributes
    - – Trivial and special example: all the relation attributes
  - **Key** = superkey with a *minimal* number of attributes
    - – I.e. **no attribute can be removed so that the identification ability would still be preserved**
    - – Multiple keys may exist in one relation
      - They even do not need to have the same number of attributes
    - – Notation: keys are underlined
      - Relation(Key, CompositeKeyPart1, CompositeKeyPart2, …)
      - **Note the difference between simple and composite keys**

Integrity Constraints

- **Referential integrity**
  - **Foreign key** = set of attributes of the referencing relation which corresponds to a (super)key of the referenced relation
    - It is usually not a (super)key in the referencing relation
    - Notation
      - ReferencingTable.foreignKey ⊆ ReferencedTable.Key
      - foreignKey ⊆ ReferencedTable.Key

Sample Relational Database

- Schema

  Course(Code, Name, …)

  Schedule(Id, Event, Day, Time, …), Event ⊆ Course.Code

- Data

Id	Event	Day	Time	…
1	A7B36DBS	THU	11:00	
2	A7B36DBS	THU	12:45	
3	A7B36DBS	THU	14:30	
4	A7B36XML	FRI	09:15	

Code	Name	…
A7B36DBS	Database systems	
A7B36XML	XML technologies	
A7B36PSI	Computer networks	

Relations vs. Tables

- Tables
  - **Table header ~ relation schema**
  - **Row ~ tuple**
  - **Column ~ attribute**
- However…
  - Tables are not sets, and so…
    - there can be duplicate rows in tables
    - rows in tables can be ordered
  - I.e. SQL and existing RDBMS do not (always) follow the formal relational model strictly

Object vs. (Object-)Relational Model

- **Relational model**
  - Data stored in flat tables
  - Suitable for data-intensive batch operations
- **Object model**
  - Data stored as graphs of objects
  - Suitable for individual navigational access to entities
- **Object-Relational model**
  - Relational model enriched by object elements
    - Attributes may be of complex data types
    - Methods can be defined on data types as well

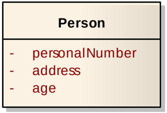
Transformation of UML / ER to RM

Conceptual Schema Transformation

- **Basic idea**
  - What we have
    - ER: entity types, attributes, identifiers, relationship types, ISA hierarchies
    - UML: classes, attributes, associations
  - What we need
    - **Schemas of relations with attributes, keys, and foreign keys**
  - How to do it
    - **Classes with attributes** → relation schemas
    - **Associations** → separate relation schemas or together with classes (depending on cardinalities…)

Classes

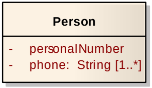
- **Class →**
  - Separate table
    - Person(<u>personalNumber</u>, address, age)



  - **Artificial keys**
    - Artificially added **integer identifiers**
      - with no correspondence in the real world
      - but with several efficiency and also design advantages
      - usually automatically generated and assigned
    - Person(<u>personId</u>, <u>personNumber</u>, address, age)

Attributes

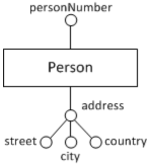
- **Multivalued attribute →**



  - Separate table
    - **Person(<u>personalNumber</u>)**
      Phone(<u>personalNumber, phone</u>)
      Phone.personalNumber ⊆ Person.personalNumber

Attributes

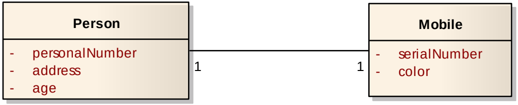
- **Composite attribute →**



  - Separate table
    - **Person(<u>personalNumber</u>)**
      Address(<u>personalNumber</u>, street, city, country)
      Address.personalNumber ⊆ Person.personalNumber
  - Sub-attributes can also be inlined
    - But only in case of (1,1) cardinality
    - **Person(<u>personNumber</u>, street, city, country)**

Binary Associations

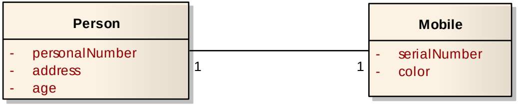
- **Multiplicity (1,1):(1,1) →**



  - Three tables (basic approach)
    - **Person(<u>personalNumber</u>, address, age)**
      Mobile(<u>serialNumber</u>, color)
      Ownership(<u>personalNumber</u>, <u>serialNumber</u>)
      Ownership.personalNumber ⊆ Person.personalNumber
      Ownership.serialNumber ⊆ Mobile.serialNumber

Binary Associations

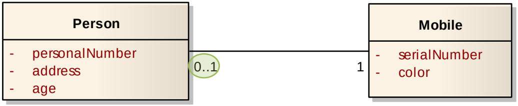
- **Multiplicity (1,1):(1,1) →**



  - Single table
    - **Person(<u>personalNumber</u>, address, age, <u>serialNumber</u>, color)**

Binary Associations

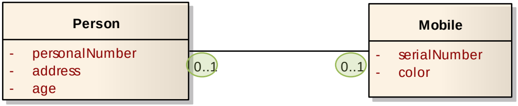
- **Multiplicity (1,1):(0,1) →**



  - Two tables
    - **Person(<u>personalNumber</u>, address, age, <u>serialNumber</u>)**
      Person.serialNumber ⊆ Mobile.serialNumber
      Mobile(<u>serialNumber</u>, color)
    - Why not just 1 table?
      - Because a mobile phone can exist independently of a person

Binary Associations

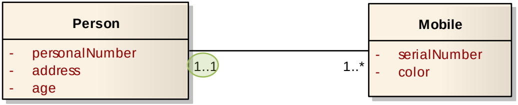
- **Multiplicity (0,1):(0,1) →**



  - Three tables
    - **Person(<u>personalNumber</u>, address, age)**
      Mobile(<u>serialNumber</u>, color)
      Ownership(<u>personalNumber</u>, <u>serialNumber</u>)
      Ownership.personalNumber ⊆ Person.personalNumber
      Ownership.serialNumber ⊆ Mobile.serialNumber
    - Note that a personal number and serial number are both independent keys in the Ownership table

Binary Associations

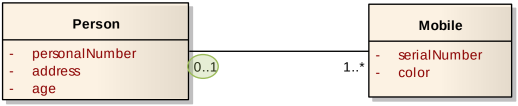
- **Multiplicity (1,n)/(0,n):(1,1) →**



- Two tables
  - **Person(<u>personalNumber</u>, address, age)**
    Mobile(<u>serialNumber</u>, color, personalNumber)
    Mobile.personalNumber ⊆ Person.personalNumber
  - Why a personal number is not a key in the Mobile table?
    - Because a person can own more mobile phones

Binary Associations

- **Multiplicity (1,n)/(0,n):(0,1) →**



  - Three tables
    - **Person(<u>personalNumber</u>, address, age)**
      Mobile(<u>serialNumber</u>, color)
      Ownership(personalNumber, <u>serialNumber</u>)
      Ownership.personalNumber ⊆ Person.personalNumber
      Ownership.serialNumber ⊆ Mobile.serialNumber
    - Why a personal number is not a key in the Ownership table?
      - Because a person can own more mobile phones

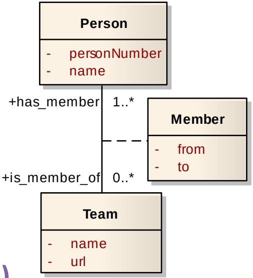
Binary Associations

- **Multiplicity (1,n)/(0,n):(1,n)/(0,n) →**

  - Three tables
    - **Person(<u>personalNumber</u>, address, age)**
      Mobile(<u>serialNumber</u>, color)
      Ownership(<u>personalNumber, serialNumber</u>)
      Ownership.personalNumber ⊆ Person.personalNumber
      Ownership.serialNumber ⊆ Mobile.serialNumber
    - Note that there is a composite key in the Ownership table

Attributes of Associations

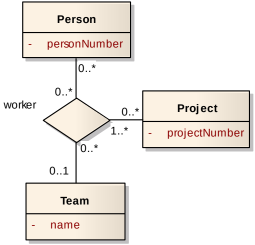
- **Attribute of an association →**
  - Stored together with a given association table
    - **Person(<u>personNumber</u>, name)**
      Team(<u>name</u>, url)
      Member(<u>personNumber, name</u>, from, to)
      Member.personNumber ⊆ Person.personNumber
      Member.name ⊆ Team.name



  - Multivalued and composite attributes are transformed analogously to attributes of ordinary classes

General Associations

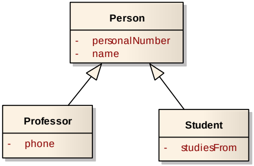
- **N-ary association →**
  - Universal solution:
    N tables for classes +
    1 association table
    - Person(<u>personNumber</u>)
      Project(<u>projectNumber</u>)
      Team(<u>name</u>)
      Worker(<u>personNumber, projectNumber, name</u>)
      Worker.personNumber ⊆ Person.personNumber
      Worker.projectNumber ⊆ Project.projectNumber
      Worker.name ⊆ Team.name



  - **Less tables?** Yes, in case of nice (1,1) cardinalities…

Hierarchies

- **ISA hierarchy →**
  - Universal solution:
    separate table for each type
    with specific attributes only



– **Person(<u>personalNumber</u>, name)**
Professor(<u>personalNumber</u>, phone)
Student(<u>personalNumber</u>, studiesFrom)
Professor.personalNumber ⊆ Person.personalNumber
Student.personalNumber ⊆ Person.personalNumber

– Applicable in any case (w.r.t. **covering / overlap constraints**)

– Pros: flexibility (when attributes are altered)

– Cons: joins (when full data is reconstructed)

Hierarchies

- **ISA hierarchy →**
  - Only one table for a hierarchy source
    - **Person(personalNumber, name, phone, studiesFrom, type)**
    - Universal once again, but **not always suitable**
      - Types of instances are distinguished by an artificial attribute
        - Enumeration or event a set
          depending on the overlap constraint
    - Pros: no joins
    - Cons: `NULL` values required (and so it is not a nice solution)

Hierarchies

- **ISA hierarchy →**
  - Separate table for each leaf type
    - **Professor(<u>personalNumber</u>, name, phone)**
      Student(<u>personalNumber</u>, name, studiesFrom)
    - This solution is **not always applicable**
      - In particular when the covering constraint is false
    - Pros: no joins
    - Cons:
      - Redundancies (when the overlap constraint is false)
      - Integrity considerations (uniqueness of a personal number)

Weak Entity Types

- **Weak entity type →**
  - Separate table
    - Institution(name)
      Team(code, name)
      Team.name ⊆ Institution.name
    - Recall that the cardinality must always be (1,1)
    - Key of the weak entity type involves also a key (any when more available) from the entity type it depends on