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# CS520
# Data Integration, Warehousing, and Provenance

## 1. Introduction

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## Outline





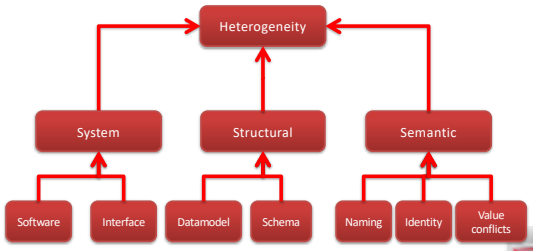
## Overview

- Topics covered in this part
  - Heterogeneity and Autonomy
  - Data Integration Tasks
  - Data Integration Architectures (Methods)
  - Some Formal Background (sorry!)



## 1.1 Heterogeneity +Autonomy

- Taxonomy of Heterogeneity






## 1.1 System Heterogeneity

- Hardware/Software
  - Different hardware capabilities of sources
  - Different protocols, binary file formats, …
  - Different access control mechanism
- Interface Heterogeneity
  - Different interfaces for accessing data from a source
    - HTML forms
    - XML-Webservices
    - Declarative language



## 1.1 System Heterogeneity

- Hardware/Software
  - Different hardware capabilities of sources
    - **Mobile phone vs. server:** Cannot evaluate cross-product of two 1GB relations on a mobile phone
  - Different protocols, binary file formats, …
    - **Order information stored in text files:** line ending differs between Mac/Window/Linux, character encoding
  - Different access control mechanism
    - **FTP-access to files:** public, ssh auth[illegible]tion, .

## 1.1 System Heterogeneity

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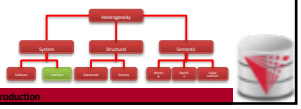
- Interface Heterogeneity
  - Different interfaces for accessing data from a source
    - HTML forms
    - Services (SOA)
    - Declarative language
    - Files
    - Proprietary network protocol
    - …





## 1.1 System Heterogeneity

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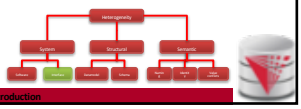
- Interface Heterogeneity – Expressiveness
  - Keyword-search vs. query language
  - **Predicates**: equality (=), inequality (<, !=)
  - **Logical connectives**: conjunctive (AND), disjunctive (OR), negation
  - **Complex operations**: aggregation, quantification
  - **Limitations**: restriction to particular tables, predicates, fixed queries with parameters, …





## 1.1 System Heterogeneity

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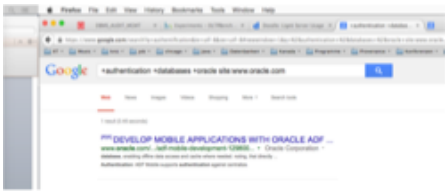
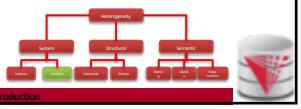
- Interface Heterogeneity – Examples
  - Google search (+/-, site:, intitle:, filetype:







## 1.1 System Heterogeneity

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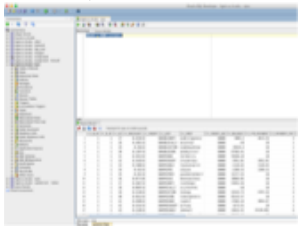
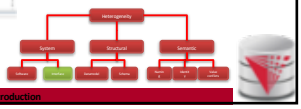
- Interface Heterogeneity – Examples
  - SQL







## 1.1 System Heterogeneity

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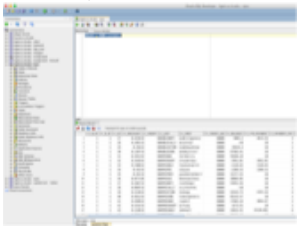
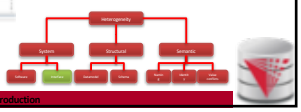
- Interface Heterogeneity – Examples
  - SQL







## 1.1 System Heterogeneity

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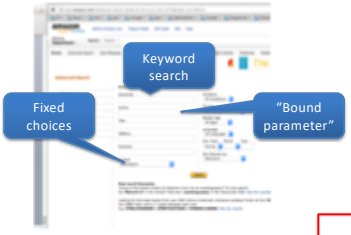
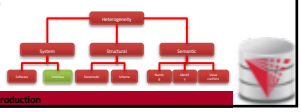
- Interface Heterogeneity – Examples
  - Web-form (with DB backend?)



## 1.1 System Heterogeneity

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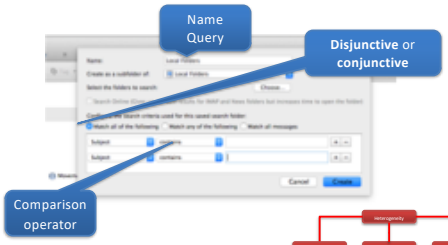
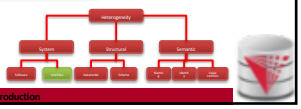
- Interface Heterogeneity – Examples
  - Email-client





## 1.1 System Heterogeneity

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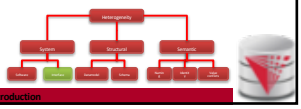
- Problems with interface heterogeneity
  - Global query language is more powerful
    - User queries may not be executable
    - Integration system has to evaluate part of the query
  - Bound parameters are incompatible with query
    - User query may not be executable





## 1.1 System Heterogeneity

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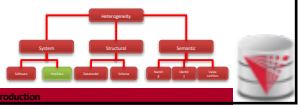
- Example: more expressive global language
  - SQL with one table
    - books (title, author, year, isbn, genre)
  - Web form for books about history shown below
  - What problems do may arise translating user queries?



## 1.1 System Heterogeneity

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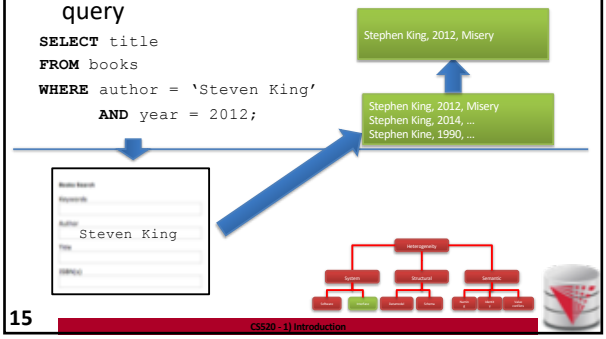
- Integration system has to process part of the query

```
SELECT title
FROM books
WHERE author = 'Steven King'
      AND year = 2012;
```






## 1.1 System Heterogeneity

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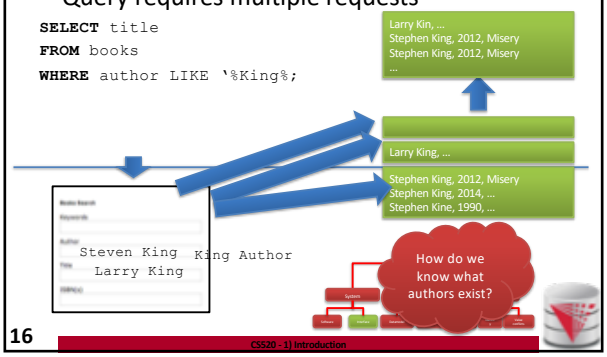
- Query requires multiple requests

```
SELECT title
FROM books
WHERE author LIKE '%King%;
```






## 1.1 System Heterogeneity

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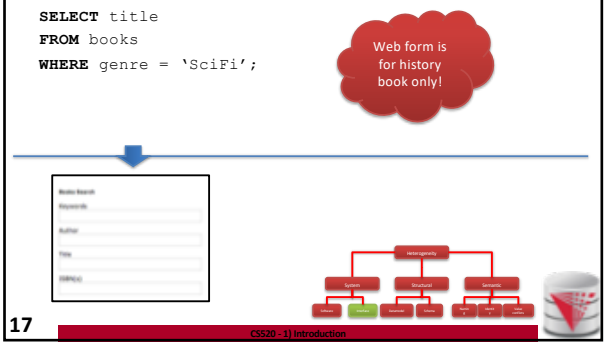
- Query cannot be answered

```
SELECT title
FROM books
WHERE genre = 'SciFi';
```



## 1.1 Heterogeneity +Autonomy

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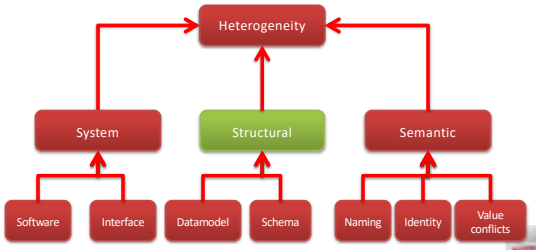
- Taxonomy of Heterogeneity






## 1.1 Structural Heterogeneity

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- **Data model**
  - Different semantic/expressiveness
  - Different structure
- **Schema**
  - **Integrity constraints, keys**
  - **Schema elements**:
    - use attribute or separate relations)
  - **Structure**:
    - e.g., normalized vs. denormalized relational schema



## 1.1 Structural Heterogeneity

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- **Data model**
  - Relational model
  - XML model
  - Object-oriented model
  - Ontological model
  - JSON
  - …



## 1.1 Structural Heterogeneity

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- Example: data model
  - Relational model
  - XML model
  - JSON
  - OO
- Person and their addresses



## 1.1 Structural Heterogeneity

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- **Schema**
  - Modeling choices
    - Relation vs. attribute
    - Attribute vs. value
    - Relation vs. value
  - Naming
  - Normalized vs. denormalized (relational concept)
  - Nesting vs. reference



## 1.1 Structural Heterogeneity

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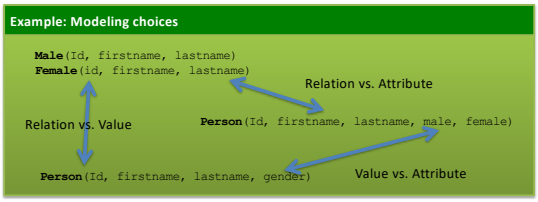


## 1.1 Structural Heterogeneity

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- **Relation-relation conflicts**
  - Naming conflicts
    - Relations with different name representing the same data (**synonym**)
    - Relations with same name representing different information (**homonym**)
  - Structural conflicts
    - Missing attributes
    - Many-to-one
    - Missing, but derivable attributes
  - Integrity constraint conflicts



## 1.1 Structural Heterogeneity

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**Example: Conflicts between relations**

```
Person(Id, firstname, lastname, male, female)
Person(Id, name, gender, birthday)
Manager(Id, name, gender, age)
```



## 1.1 Structural Heterogeneity

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Mutliple attribtue vs one attribute

**Example: Conflicts between relations**

```
Person(Id, firstname, lastname, male, female)
Person(Id, name, gender, birthday)
Manager(Id, name, gender, age)
```

Missing derivable attribute: Role

Derivable attribute: Compute age from birthday



## 1.1 Structural Heterogeneity

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- **Attribute-attribute conflicts**
  - Naming conflicts
    - Attributes with different name representing the same data (**synonym**)
    - Attributes with same name representing different information (**homonym**)
  - Default value conflict
  - Integrity constraint conflicts
    - Datatype
    - Constraints restricting values



## 1.1 Structural Heterogeneity

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**Example: Conflicts between attributes and attributes**

| SSN | FirstName VARCHAR(40) | LastName | Age CHECK(Age > 18) |
|---|---|---|---|
| 333-333-3333 | Peter | Schmeter | 30 |
| 333-333-9999 | Hans | Glanz | NULL |

| SSN | FirstName VARCHAR(25) | SurName | Age |
|---|---|---|---|
| 3333333333 | Peter | Schmeter | 30 |
| 3333339999 | Hans | Glanz | -1 |



## 1.1 Structural Heterogeneity

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**Example: Conflicts between attributes and attributes**

| SSN | FirstName VARCHAR(40) | LastName | Age CHECK(Age > 18) |
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| SSN | FirstName VARCHAR(25) | SurName | Age |
|---|---|---|---|
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| 3333339999 | Hans | Glanz | -1 |

Conflicting constraint

Conflicting default value

Conflicting format

Conflicting datatype

synonym

## 1.1 Structural Heterogeneity

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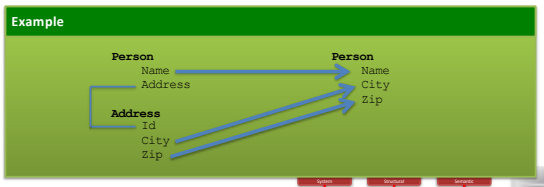
- **Normalized vs. denormalized**
  - E.g., relational model: Association between entities can be represented using multiple relations and foreign keys or one relation






## 1.1 Structural Heterogeneity

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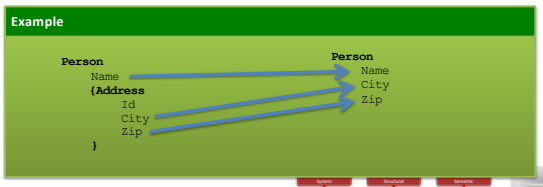
- **Nested vs. flat**
  - Association between entities can be represented using nesting or references (previous slides)






## 1.1 Structural Heterogeneity

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- **Problems caused by schema heterogeneity**
  - Unified access to multiple schemas or integrate schemas into new schema
    - **Schema level**: schema mapping, model management operators, schema languages
    - **Data Level:** virtual data integration, data exchange, warehousing (ETL)



## 1.1 Heterogeneity +Autonomy

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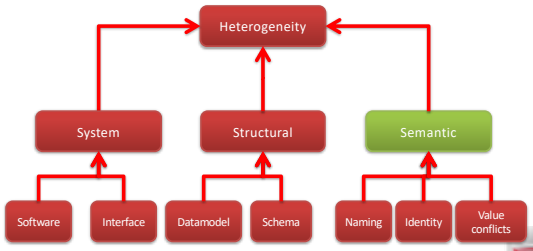
- Taxonomy of Heterogeneity






## 1.1 Semantic Heterogeneity

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- **Semantic Heterogeneity**
  - Naming Conflicts
  - Identity Conflicts (Entity resolution)
  - Value Conflicts (Data Fusion)



## 1.1 Semantic Heterogeneity

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- **Naming Conflicts**
  - Ontological (concepts)
    - Birds vs. Animals
  - Synonyms
    - Surname vs. last name
  - Homonyms
  - Units
    - Gallon vs. liter
  - Values
    - Manager vs. Boss

## 1.1 Semantic Heterogeneity

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- **Ontological concepts**
  - Relationships between concepts
    - **A = B** - Equivalence
    - **A ⊆B** - Inclusion
    - **A ∩ B** - Overlap
    - **A ≠ B** - Disjunction



## 1.1 Semantic Heterogeneity

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- **Ontological concepts**
  - Relationships between concepts
    - **A = B** - Equivalence
    - **A ⊆B** - Inclusion
    - **A ∩ B** - Overlap
    - **A ≠ B** - Disjunction

**Example**

**Equivalence:** Human vs Homo sapiens
**Inclusion:** Bird vs Animal
**Overlap:** Animal vs aquatic lifeform
**Disjunction:** Fish vs Mamal



## 1.1 Semantic Heterogeneity

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- **Naming concepts (synonyms)**
  - **Different** words with **same meaning**

**Example**

**Person** (Name, Age)

**Human** (LastName, Age)



## 1.1 Semantic Heterogeneity

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- **Naming concepts (homonyms)**
  - **Same** words with **different meaning**

**Example**

**Person** (Title, Name)

**Movie** (Title, Year)



## 1.1 Semantic Heterogeneity

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- **Naming concepts (units)**

**Example**

**Person** (Title, Name, Salary) — $

**Person** (Title, Name, Salary) — CAD



## 1.1 Semantic Heterogeneity

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- Identity Conflicts
  - What is an object?
    - E.g., multiple tuples in relational model
  - Central question:
    - Does object A represent the same entity as B
  - This problem has been called
    - **Entity resolution**
    - **Record linkage**
    - **Deduplication**
    - …

## 1.1 Semantic Heterogeneity

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- Identity Conflicts

**Example**

(IBM, 300000000, USA)

(International Business Machines Corporation, 50000)



## 1.1 Semantic Heterogeneity

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- **Value Conflicts**
  - Objects representing the same entities have conflicting values for semantically equivalent attributes
    - We have to identified that these objects are represent the same entitity first!
  - Resolving such conflicts requires **Data Fusion**
    - Pick value from conflicting values
    - Numerical methods: e.g., average
    - Preferred value
    - …



## 1.1 Autonomy

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- **How autonomous are data sources**
  - One company
    - Can enforce, e.g., schema and software
  - …
  - The web
    - Website decides
      - Interface
      - Determines access restrictions and limits
      - Availability
      - Format
      - Query restrictions
      - …



## 1.2 Data integration tasks

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- **Cleaning and prepreparation**
- **Entity resolution**
- **Data Fusion**
- **Schema matching**
- **Schema mapping**
- **Query rewrite**
- **Data translation**



## 1.3 Data integration architectures

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- **Virtual data integration**
- **Data Exchange**
- **Peer-to-peer data integration**
- **Datawarehousing**
- **Big Data analytics**



## 1.4 Formal Background

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- **Query Equivalence**
  - Complexity for different query classes
- **Query Containment**
  - Complexity for different query classes
- **Datalog**
  - Recursion + Negation
- **Integrity Constraints**
  - Logical encoding of integrity constraints
- **Similarity Measures/Metrics**

## 1.4 Integrity constraints

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- **You know some types of integrity constraints already**
  - **Functional dependencies**
    - **Keys are a special case**
  - **Foreign keys**
    - **We have not really formalized that**



## 1.4 Integrity constraints

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- Other types are
  - Conditional functional dependencies
    - **E.g., used in cleaning**
  - Equality-generating dependencies
  - Multi-valued dependencies
  - Tuple-generating dependencies
  - Join dependencies
  - Denial constraints
  - …



## 1.4 Integrity constraints

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- How to manage all these different types of constraints?
  - Has been shown that these constraints can be expressed in a logical formalism.
  - Formulas which consist of relational and comparison atoms. Variables represent values
    - R(x,y,z)
    - x = y



## 1.4 Integrity Constraints

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**Example**

**Primary Key R(A,B):**

$$\forall x, y, z : R(x, y) \wedge R(x, z) \rightarrow y = z$$

**Functional Dependency R(A,B) with A->B:**

$$\forall x, y, z, a : R(x, y) \wedge R(z, a) \wedge x = z \rightarrow y = a$$

**Foreign Key R(A,B), S(C,D) where D is FK to R:**

$$\forall x, y : S(x, y) \rightarrow \exists z : R(y, z)$$



## 1.4 Integrity constraints

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- Types of constraints we will use a lot
  - Tuple-generating dependencies (**tgds**)
    - Implication with conjunction of relational atoms
    - Foreign keys and schema mappings (later)

$$\forall \vec{x} : \phi(\vec{x}) \rightarrow \exists \vec{y} : \psi(\vec{x}, \vec{y})$$

  - Equality-generating dependencies (**egds**)
    - Generalizes keys, FDs

$$\forall \vec{x} : \phi(\vec{x}) \rightarrow \wedge_{k=1}^{n} x_{i_k} = x_{j_k}$$



## 1.4 Datalog

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- What is datalog?
  - Prolog for databases (syntax very similar)
  - A logic-based query language
- Queries (Program) expressed as set of rules

$$Q(\vec{x}) : -R_1(\vec{x_1}), \ldots, R_n(\vec{x_n}).$$

- One Q is specified as the answer relation (the relation returned by the query)

## 1.4 Datalog - Intuition

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- A **Datalog rule**

$$Q(\vec{x}) :- R_1(\vec{x_1}), \ldots, R_n(\vec{x_n}).$$

- For all bindings of variables in the right-hand side (RHS) that makes the RHS true (conjunction) return bindings of $\vec{x}$

**Example**

```
Q(Name):- Person(Name,Age).
Return names of persons
```



## 1.4 Datalog - Syntax

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- A **Datalog program** is a set of datalog rules
  - Optionally a distinguished answer predicate
- A **Datalog rule** is

$$Q(\vec{x}) :- R_1(\vec{x_1}), \ldots, R_n(\vec{x_n}).$$

- **X's** are lists of variables and constants
- **Ri's** are relation names
- **Q** is a relation name



## 1.4 Datalog - Terminology

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- Left-hand side of a rule is called it's **head**
- Right-hand side of a rule is called it's **body**
- Relation are called **predicates**
- $R(\vec{x})$ is called an **atom**
- An **instance** I of a database is the data
- The **active domain** adom(I) of an instance I is the set of all constants that occur in I

$$Q(\vec{x}) :- R_1(\vec{x_1}), \ldots, R_n(\vec{x_n}).$$



## 1.4 Datalog - Terminology

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**Example**

```
Q(N):- Person(N,A).

N, A are variables
Q(N), Person(N,A) are atoms
Person and Q are predicates
```

| Name | Age |
|---|---|
| peter | 34 |
| bob | 45 |

```
Activate domain
adom(I) = {peter,bob,34,45}
```



## 1.4 Datalog - Terminology

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- **Intensional** vs. **extensional**
  - Extensional database (**edb**)
    - What we usually call database
  - Intensional database (**idb**)
    - Relations that occur in the head of rules (are populated by the query)
  - Usually we assume that these do not overlap

$$Q(\vec{x}) :- R_1(\vec{x_1}), \ldots, R_n(\vec{x_n}).$$



## 1.4 Datalog - Safety

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- A datalog program is safe if all its rules are **safe**
- A rule is **safe** if all variables in $\vec{x}$ occur in at least one $\vec{x_i}$

$$Q(\vec{x}) :- R_1(\vec{x_1}), \ldots, R_n(\vec{x_n}).$$

**Example**

```
Q(Name):- Person(Name,Age).   (safe)
Q(Name,Sal):-Peron(Name,Age). (unsafe)
```

## 1.4 Datalog - Semantics

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- The instance of an idb predicate Q in a datalog program for an edb instance I contains all facts that can be derived by applying rules with Q in the head
- A rule derives a fact Q(c) if we can find a binding of variables of the rule to constants from adom(I) such that x is bound to c and the body is true

$$Q(\vec{x}) : -R_1(\vec{x_1}), \ldots, R_n(\vec{x_n}).$$



## 1.4 Datalog - Semantics

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**Example**

```
Q(N):- Person(N,A).

N=peter,A=peter: Q(peter):- Person(peter,peter).
N=peter,A=bob: Q(peter):- Person(peter,bob).
N=peter,A=34: Q(peter):- Person(peter,34).
N=bob,A=peter: Q(bob):- Person(peter,peter).
N=bob,A=bob: Q(bob):- Person(peter,bob).
N=bob,A=34: Q(bob):- Person(bob,34).
N=34,A=peter: Q(34):- Person(34,peter).
N=34,A=bob: Q(34):- Person(34,bob).
N=34,A=34: Q(34):- Person(34,34).
```

| N |
|---|
| peter |
| bob |

**Active domain**

```
adom(I) = {peter,bob,34}
```

| Name | Age |
|---|---|
| peter | 34 |
| bob | 34 |



## 1.4 Datalog

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- Different flavors of datalog
  - **Conjunctive query**
    - Only one rule
    - Expressible as Select-project-join (SPJ) query in relational algebra (only equality and AND in selection)
  - **Union of conjunctive queries**
    - Also allow union
    - SPJ + set union in relational algebra
    - Rules with the same head in Datalog
  - **Conjunctive queries with inequalities**
    - Also allow inequivalities, e.g., <



## 1.4 Datalog

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- Different flavors of datalog
  - **Recursion**
    - Rules may have recursion:
      - E.g., head predicate in the body
    - Fix point semantics based on immediate consequence operator
  - **Negation (first-order queries)**
    - Negated relational atoms allowed
    - Require that every variable used in a negated atom also occurs in at least on positive atom (**safety**)
  - **Combined Negation + recursion**
    - Stronger requirements (e.g., stratification)



## 1.4 Datalog – Semantics (Negation)

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- A rule derives a fact Q(c) if we can find a binding of variables of the rule to constants from adom(I) such that x is bound to c and the body is true
- A negated atom not R(X) is true if R(X) is not part of the instance

$$Q(\vec{x}) : -R_1(\vec{x_1}), \ldots, R_n(\vec{x_n}).$$



## 1.4 Datalog - Semantics

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**Example**

```
Q(N):- Person(N,A), not Lives(N).

N=peter,A=peter: Q(peter):- Person(peter,peter),
                            not Lives(peter).
N=peter,A=bob: Q(peter):- Person(peter,bob),
                          not Lives(peter).
...
N=peter,A=34: Q(bob):- Person(bob,34),
                       not Lives(bob).
...
```

**Result**

| N |
|---|
| bob |

**Lives**

| Name |
|---|
| peter |

**Person**

| Name | Age |
|---|---|
| peter | 34 |
| bob | 34 |

**Active domain**

```
adom(I) = {peter,bob,34}
```

## 1.4 Datalog

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**Example**

Relation **hop(A,B)** storing edges of a graph.

```
Q2hop(x,z): hop(x,y),hop(x,z).

Qreach(x,y): hop(x,y).
Qreach(x,z): Qreach(x,y),Qreach(y,z).

Qnode(x): hop(x,y).
Qnode(x): hop(y,x).
```



## 1.4 Datalog

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**Example**

Relation **hop(A,B)** storing edges of a graph.

```
Qnode(x): hop(x,y).
Qnode(x): hop(y,x).

QnotReach(x,y): Qnode(x), Qnode(y),
                not Qreach(x,y).
```



## 1.4 Containment and Equivalence

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**Definition: Query Equivalence**

Query Q is equivalent to Q' iff for every database instance I both queries return the same result

$$Q \equiv Q' \Leftrightarrow \forall I : Q(I) = Q'(I)$$

**Definition: Query Containment**

Query Q is contained in query Q' iff for every database instance I the result of Q is contained in the result of Q'

$$Q \sqsubseteq Q' \Leftrightarrow \forall I : Q(I) \subseteq Q'(I)$$



## 1.4 Equivalence

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- The problem of checking query equivalence is of different complexity depending on the **query language** and whether we consider **set or bag semantics**



## 1.4 Containment and Equiv.

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**Example**

```
Q1(x,y): R(x,y), R(x,z).
Q2(x,y): R(x,y).
Q3(x,x): R(x,x).
Q4(x,y): R(x,y).
Q5(x,x): R(x,y), R(x,x).
Q6(x,z): R(x,y), R(y,z).
```



## 1.4 Containment and Equiv.

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**Example**

Relation **hop(A,B)** storing edges of a graph.

```
Q2hop(x,z): hop(x,y),hop(x,z).

Qup2Hop(x,z): hop(x,y),hop(x,z).
Qup2Hop(x,z): hop(x,z).

Qsym(x,y): hop(x,y).
Qsym(x,y): hop(y,x).
Qsym2Hop(x,y): Qsym(x,y),Qsym(y,z).
```

## 1.4 Complexity of Eq. and Cont.

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| Set semantics | Relational Algebra | Conjunctive Queries (CQ) | Union of Conjunctive Queries (UCQ) | Monotone Queries/ CQ≠ |
|---|---|---|---|---|
| Query Evaluation (Combined Complexity) | PSPACE-complete | NP-complete | NP-complete | NP-complete |
| Query Evaluation (Data Complexity) | LOGSPACE (that means in P) | LOGSPACE (that means in P) | LOGSPACE (that means in P) | LOGSPACE (that means in P) |
| Query Equivalence | Undecidable | NP-complete | NP-complete | $\Pi_2^P$-complete |
| Query Containment | Undecidable | NP-complete | NP-complete | $\Pi_2^P$-complete |



## 1.4 Complexity of Eq. and Cont.

ILLINOIS INSTITUTE OF TECHNOLOGY

| Bag semantics | Relational Algebra | Conjunctive Queries (CQ) | Union of Conjunctive Queries (UCQ) |
|---|---|---|---|
| Query Equivalence | Undecidable | Equivalent to graph isomorphism | Undecidable |
| Query Containment | Undecidable | **Open Problem** | Undecidable |



## 1.4 Containment Mappings

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- NP-completeness for set semantics CQ and UCQ for the containment, evaluation, and equivalence problems is based on reducing these problems to the same problem
  - **[Chandra & Merlin, 1977]**
- Notational Conventions:
  - **head(Q)** = variables in head of query Q
  - **body(Q)** = atoms in body of Q
  - **vars(Q)** = all variable in Q



## 1.4 Boolean Conjunctive Queries

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- A conjunctive query is boolean if the head does not have any variables
  - **Q() :- hop(x,y), hop(y,z)**
  - We will use Q :- … as a convention for Q() :- …
  - What is the result of a boolean query
    - Empty result **{}**, e.g., no **hop(x,y), hop(y,z)**
    - If there are tuples matching the body, then a tuple with zero attributes is returned **{()}**
  - -> We interpret {} as **false** and {()} as **true**
  - Boolean query is essentially an existential check



## 1.4 Boolean Conjunctive Queries

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- BCQ in SQL

**Example**

```
Hop relation: Hop(A,B)

Q :- hop(x,y)

SELECT EXISTS (SELECT * FROM hop)

Note: in Oracle and DB2 we need a
from clause
```



## 1.4 Boolean Conjunctive Queries

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**Example**

```
SELECT
     CASE WHEN EXISTS (SELECT *
                       FROM hop)
     THEN 1 ELSE 0
     END AS x
FROM dual;

Notes:
- Oracle and DB2 FROM not optional
- Oracle has no boolean datatype
```

## 1.4 Boolean Conjunctive Queries

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- BCQ in SQL

**Example**

```
Q :- hop(x,y), hop(y,z)

SELECT EXISTS
     (SELECT *
     FROM hop l, hop r
     WHERE l.B = r.A)
```



## 1.4 Containment Mappings

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- How to check for containment of CQs (set)

**Definition: Variable Mapping**

A variable mapping ψ from query Q to query Q' maps the variables of Q to constants or variables from Q'

**Definition: Containment Mapping**

A containment mapping from query Q to Q' is a variable mapping ψ such that:

$$\Psi(head(Q)) = head(Q')$$

$$\forall R(\vec{x_i}) \in body(Q) : \Psi(R(\vec{x_i})) \in body(Q')$$



## 1.4 Containment Mappings

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**Theorem: Containment Mappings and Query Containment**

Query Q is contained in query Q' iff there exists a containment mapping ψ from Q' to Q

$$Q \sqsubseteq Q' \Leftrightarrow \exists \Psi : \Psi \text{ is a containment mapping } Q' \to Q$$

**Example**

```
Q1(u,z): R(u,z).
Q2(x,y): R(x,y).
```

Can we find a containment mapping?



## 1.4 Containment Mappings

ILLINOIS INSTITUTE OF TECHNOLOGY

**Theorem: Containment Mapping and Query Containment**

Query Q is contained in query Q' iff there exists a containment mapping ψ from Q' to Q

**Example**

```
Q1(u,z): R(u,z).
Q2(x,y): R(x,y).

Q1 -> Q2 :Ψ(u)=x, Ψ(z)=y
Q2 -> Q1 :Ψ(x)=u, Ψ(y)=z
```



## 1.4 Containment Mappings

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**Example**

```
Q1(a,b): R(a,b), R(b,c).
Q2(x,y): R(x,y).
```



## 1.4 Containment Mappings

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**Example**

```
Q1(a,b): R(a,b), R(b,c).
Q2(x,y): R(x,y).

Do containment mappings exist?

Q1 -> Q2: none exists
Q2 -> Q1: Ψ(x)=a, Ψ(y)=b
```

## 1.4 Containment Mappings

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**Example**

$Q_1(a,b)$ : R(a,b), R(c,b).
$Q_2(x,y)$ : R(x,y).

$Q_1$ -> $Q_2$ :Ψ(a)=x, Ψ(b)=y, Ψ(c)=x
$Q_2$ -> $Q_1$ :Ψ(x)=a, Ψ(y)=b



## 1.4 Containment Background

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- It was shown that query evaluation, containment, equivalence as all reducible to homomorphism checking for CQ
  - Canonical conjunctive query $Q^I$ for instance I
    - Interpret attribute values as variables
    - The query is a conjunction of all atoms for the tuples
    - **I = {hop(a,b), hop(b,c)} -> $Q^I$ :- hop(a,b), hop(b,c)**
  - Canonical instance $I^Q$ for query Q
    - Interpret each conjunct as a tuple
    - Interpret variables as constants
    - **Q :- hop(a,a) -> $I^Q$ = {hop(a,a)}**



## 1.4 Containment Background

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- Containment Mapping <-> Containment
- Proof idea (boolean queries)
  - (if direction)
    - Assume we have a containment mapping $Q_1$ to $Q_2$
    - Consider database D
    - $Q_2(D)$ is true then we can find a mapping from vars($Q_2$) to D
    - Compose this with the containment mapping and prove that this is a result for $Q_1$



## 1.4 Containment Mappings

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**Example**

$Q_1()$ : R(a,b), R(c,b).
$Q_2()$ : R(x,y).
$Q_2$ -> $Q_1$ :Ψ(x)=a, Ψ(y)=b

D={R(1,1), R(1,2)}

$Q_1(D)$={(1,1),(1,2)}
φ(a)=1, φ(b)=2, φ(c)=1

Ψφ(x)=1, Ψφ(y)=2



## 1.4 Containment Background

ILLINOIS INSTITUTE OF TECHNOLOGY

- Containment Mapping <-> Containment
- Proof idea (boolean queries)
  - (only-if direction)
    - Assume $Q_2$ contained in $Q_1$
    - Consider canonical (frozen) database $I^{Q2}$
    - Evaluating $Q_1$ over $I^{Q2}$ and taking a variable mapping that is produced as a side-effect gives us a containment mapping



## 1.4 Containment Mappings

ILLINOIS INSTITUTE OF TECHNOLOGY

**Example**

$Q_1()$ : R(a,b), R(c,b).
$Q_2()$ : R(x,y).
$Q_2$ -> $Q_1$ :Ψ(x)=a, Ψ(y)=b

$I^{Q1}$ = {(a,b),(c,b)}

$Q_2(I^{Q1})$={()}
φ(x)=a, φ(y)=b

φ is our containment mapping Ψ

## 1.4 Containment Background

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- If you are not scared and want to know more:
  - Look up Chandra and Merlins paper(s)
  - The text book provides a more detailed overview of the proof approach
  - Look at the slides from Phokion Kolaitis excellent lecture on database theory
    - https://classes.soe.ucsc.edu/cmps277/Winter10/



## 1.4 Containment Background

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- A more intuitive explanation why containment mappings work
  - Variable naming is irrelevant for query results
  - If there is a containment mapping Q to Q'
    - Then every condition enforced in Q is also enforced by Q'
    - Q' may enforce additional conditions



## 1.4 Containment Mappings

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**Example**

$Q_1()$: **R(a,b)**, R(c,b).
$Q_2()$: **R(x,y)**.
$Q_2$ -> $Q_1$ :Ψ(x)=a, Ψ(y)=b

If there exists tuples
R(a,b) and R(c,b)
in R that make $Q_1$ true, then we take
R(a,b)
to fulfill $Q_2$



## 1.4 Containment Background

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- From boolean to general conjunctive queries
  - Instead of returning true or false, return bindings of variables
  - Recall that containment mappings enforce that the head is mapped to the head
  - -> same tuples returned, but again Q' s condition is more restrictive



## 1.4 Containment Mappings

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**Example**

$Q_1$(**a**): **R(a,b)**, R(c,b).
$Q_2$(**x**): **R(x,y)**.
$Q_2$ -> $Q_1$ :Ψ(x)=a, Ψ(y)=b

For every
R(a,b) and R(c,b)
$Q_1$ returns (a) and for every
R(a,b)
$Q_2$ returns (a)



## 1.4 Similarity Measures

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- **Problem faced by multiple integration tasks**
  - Given two objects, how similar are they
  - **E.g., given two attribute names in schema matching, given two values in data fusion/entity resolution, …**

## 1.4 Similarity Measures

ILLINOIS INSTITUTE OF TECHNOLOGY

- **Object models**
  - **Multidimensional (feature vector model)**
    - Object is described as a vector of values - one for each dimension out of a given set of dimensions
    - E.g., Dimensions are gender (male/female), age (0-120), and salary (0-1,000,000). An example object is [male,80,70,000]
  - **Strings**
    - E.g., how similar is "Poeter" to "Peter"
  - **Graphs and Trees**
    - E.g., how similar are two XML models



## 1.4 Similarity Measures

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**Definition: Similarity Measure**

Function d(p,q) where p and q are objects, that returns a real score with
- d(p,p) = 0
- d(p,q) >= 0
- Note: often scores are normalized to the range [0,1]



## 1.4 Similarity Measures

ILLINOIS INSTITUTE OF TECHNOLOGY

**Example**

**String equality:** d(p,q) = 0 if p=q strings d(p,q) = 1 else

**Euclidian distance:** d(p,q) = N-dimensional space $\sqrt{\sum_{i=1}^{n}(p[i]-q[i])^2}$

**Edit distance:** d(p,q) = minimum number of strings single character insertions, deletions, replacements to transform p into q



## 1.4 Similarity Measures

ILLINOIS INSTITUTE OF TECHNOLOGY

**Definition: Metric**

Function d(p,q) where p and q are objects, that returns a real score with

| | |
|---|---|
| **Non-negative** | d(p,q) >= 0 |
| **Symmetry** | d(p,q) = d(q,p) |
| **Identity of indiscernibles** | d(p,q) = 0 iff p=q |
| **Triangle inequality** | d(p,q) + d(q,r) >= d(p,r) |



## 1.4 Similarity Measures

ILLINOIS INSTITUTE OF TECHNOLOGY

**Definition: Metric**

Function d(p,q) where p and q are objects, that returns a real score with

| | |
|---|---|
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| **Identity of indiscernibles** | d(p,q) = 0 iff p=q |
| **Triangle inequality** | d(p,q) + d(q,r) >= d(p,r) |



## 1.4 Similarity Measures

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- **Why do we care whether d is a metric?**
  - Some data mining algorithms only work for metrics
    - **E.g., some clustering algorithms such as k-means**
    - **E.g., clustering has been used in entity resolution**
  - Metric spaces allow optimizations of some methods
    - **E.g., Nearest Neighboorhood-search: find the most similar object to an object p. This problem can be efficiently solved using index structures that only apply to metric spaces**

## Summary

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- Heterogeneity
  - Types of heterogeneity
  - Why do they arise?
  - Hint at how to address them
- Autonomy
- Data Integration Tasks
- Data Integration Architectures
- Background
  - Datalog + Query equivalence/containment + Similarity + Integrity constraints



## Outline

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0) Course Info
1) Introduction
**2) Data Preparation and Cleaning**
3) Schema matching and mapping
4) Virtual Data Integration
5) Data Exchange
6) Data Warehousing
7) Big Data Analytics
8) Data Provenance