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CS520 Data Integration, Warehousing, and Provenance

1. Introduction

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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

Overview

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

1.1 Heterogeneity +Autonomy

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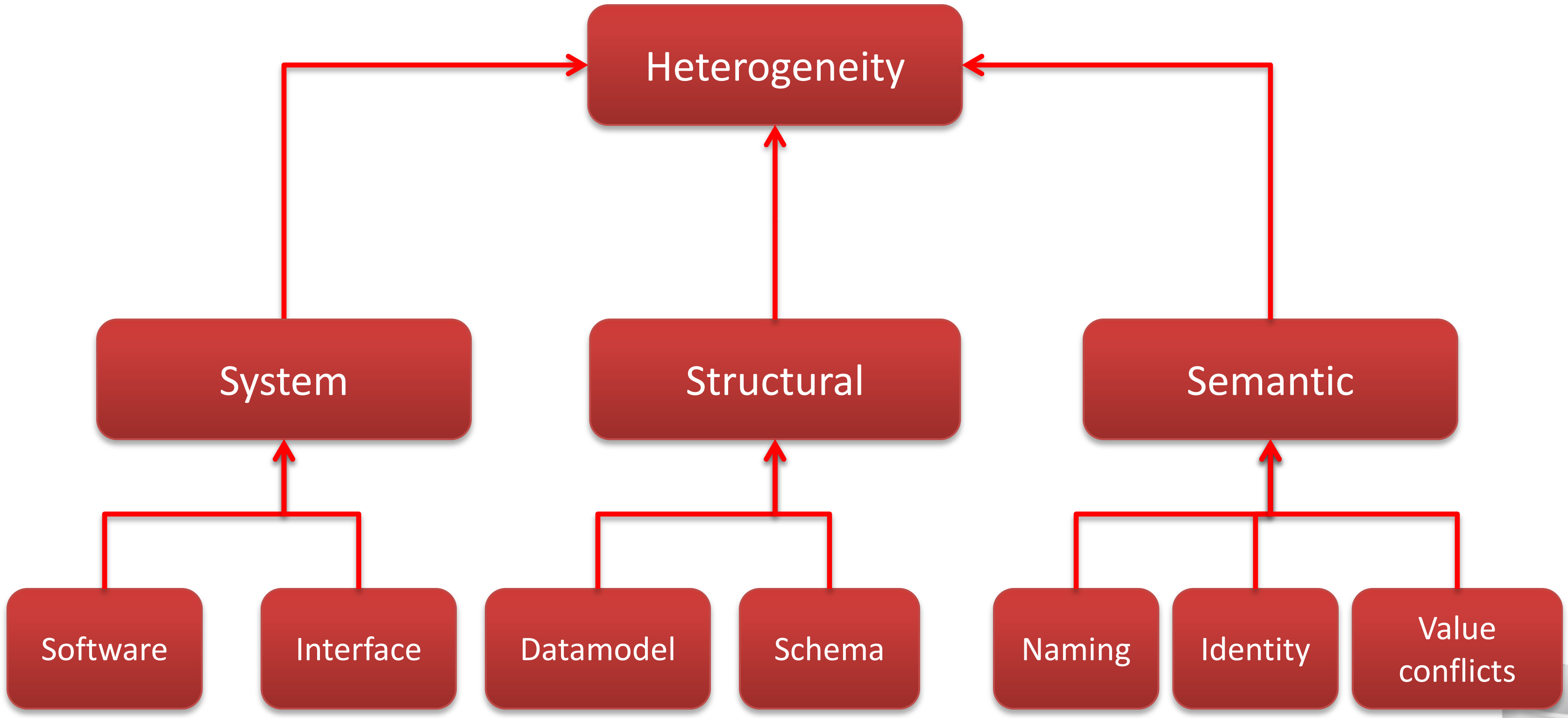
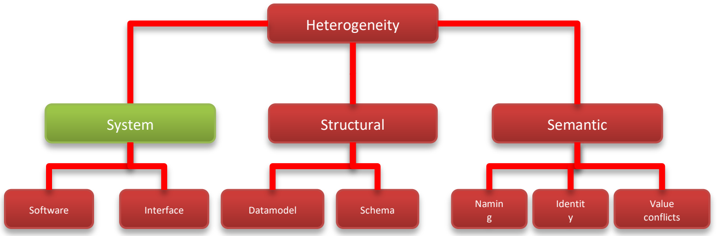
- Taxonomy of Heterogeneity



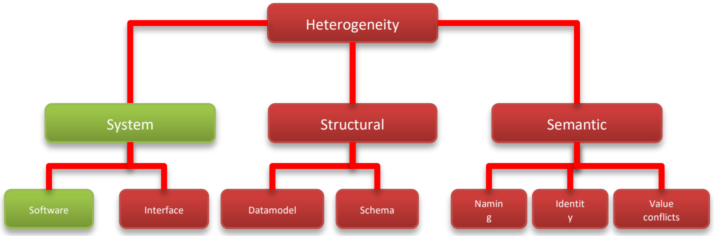
1.1 System Heterogeneity

- 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 authentication, ..



1.1 System Heterogeneity

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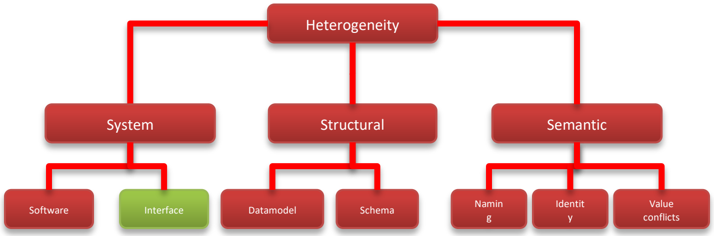
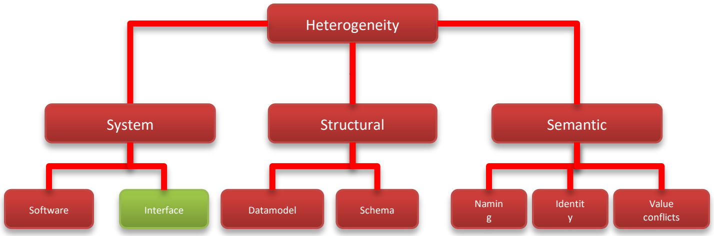
- Interface Heterogeneity
  - Different interfaces for accessing data from a source
    - HTML forms
    - Services (SOA)
    - Declarative language
    - Files
    - Proprietary network protocol
    - …



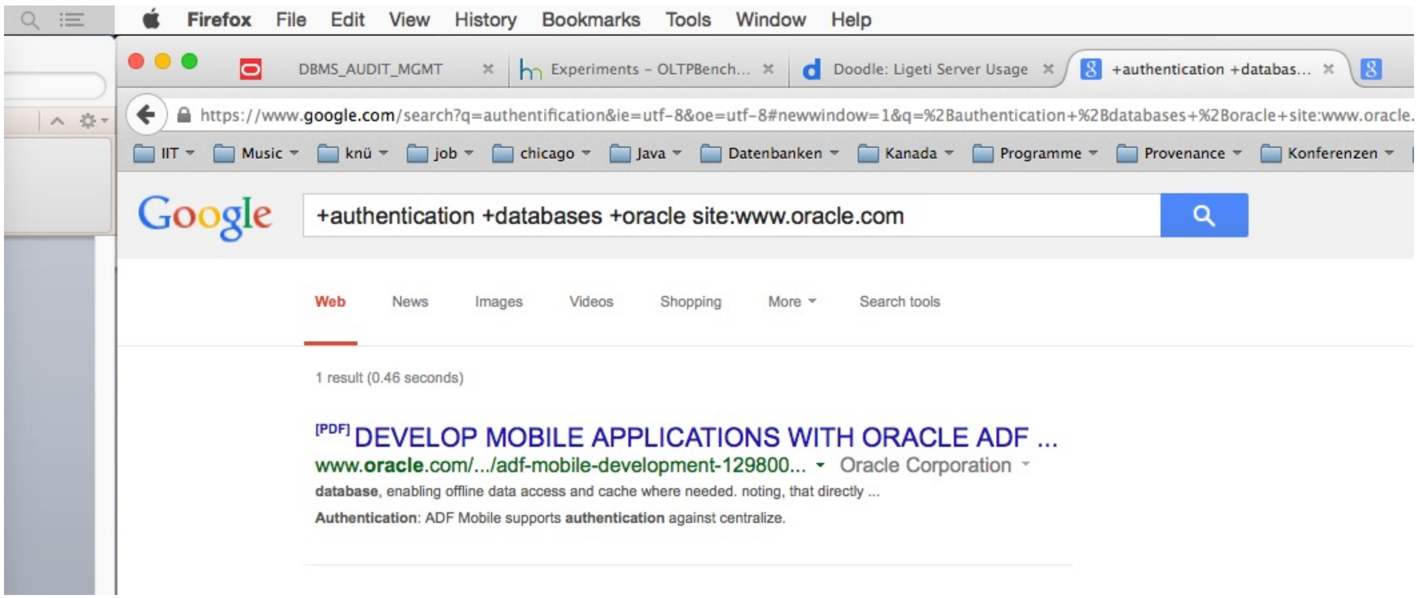
1.1 System Heterogeneity

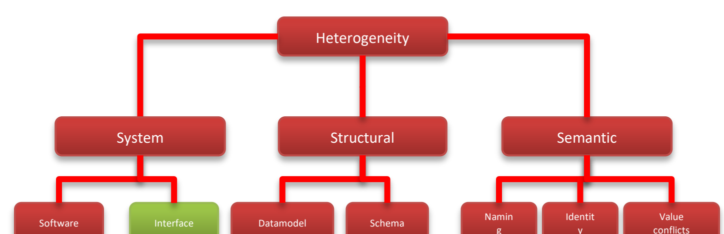
- Interface Heterogeneity – Expressiveness
  - Keyword-search vs. query language
  - **Predicates**: equality (=), inequality (<, !=)
  - **Logical connectives**: conjunctive (AND), disjunctive (OR), negation
  - **Complex operations**: aggregation, quantification
  - **Limitations**: restriction to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



1.1 System Heterogeneity

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





1.1 System Heterogeneity

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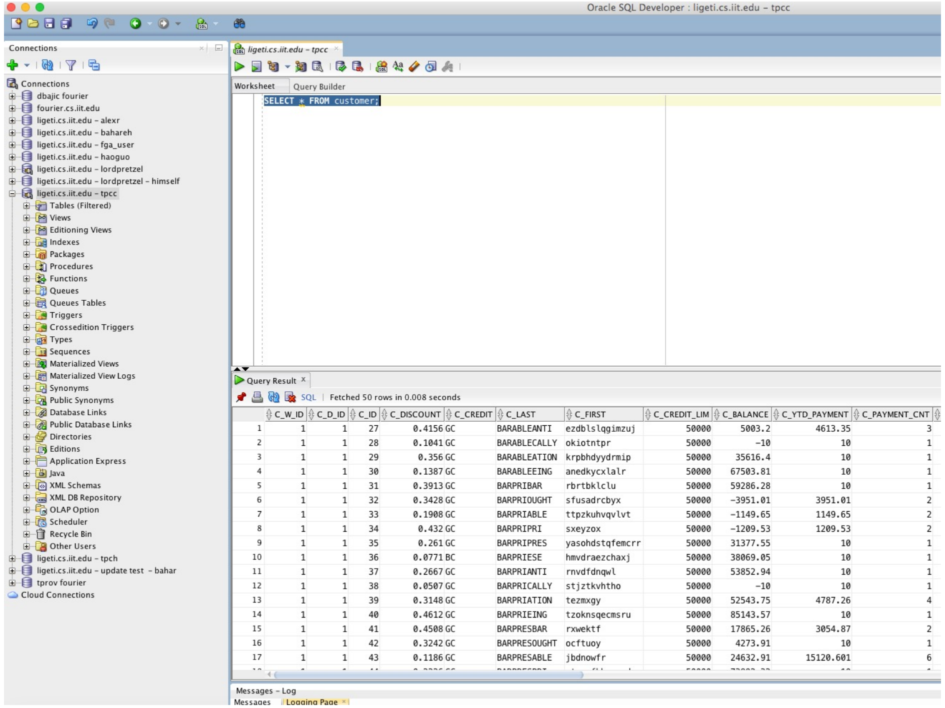
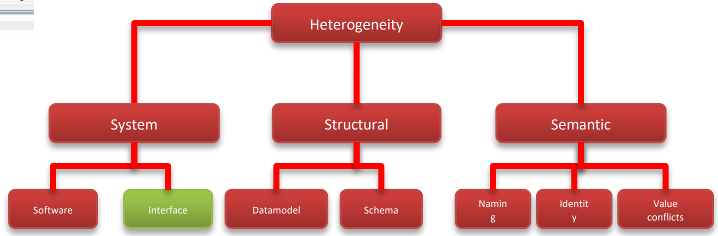
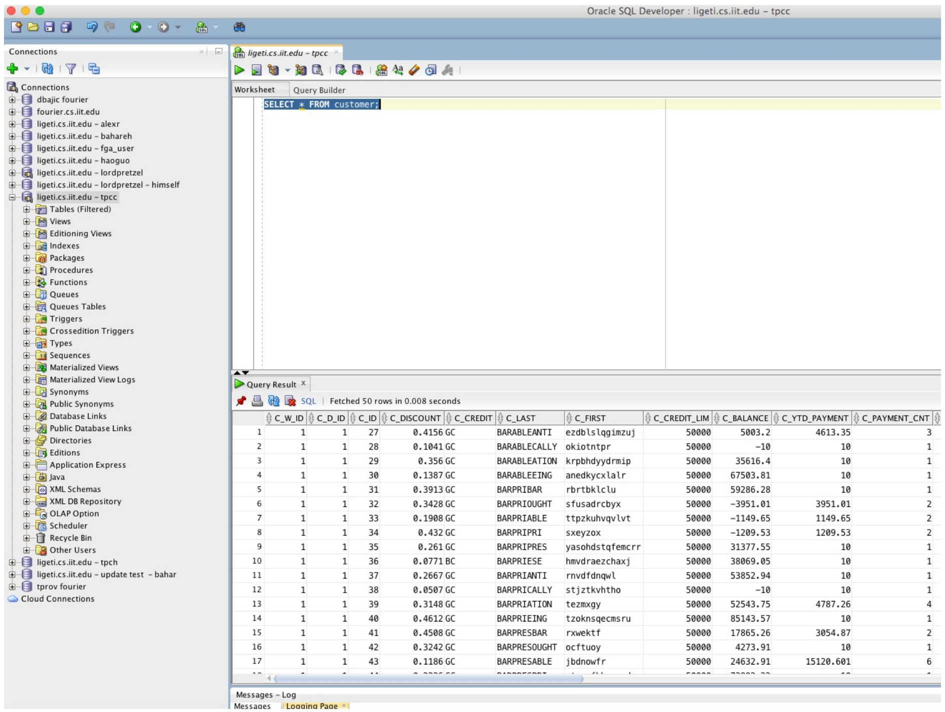
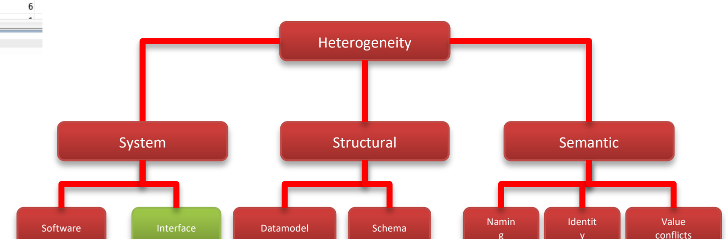
- Interface Heterogeneity – Examples
  - SQL



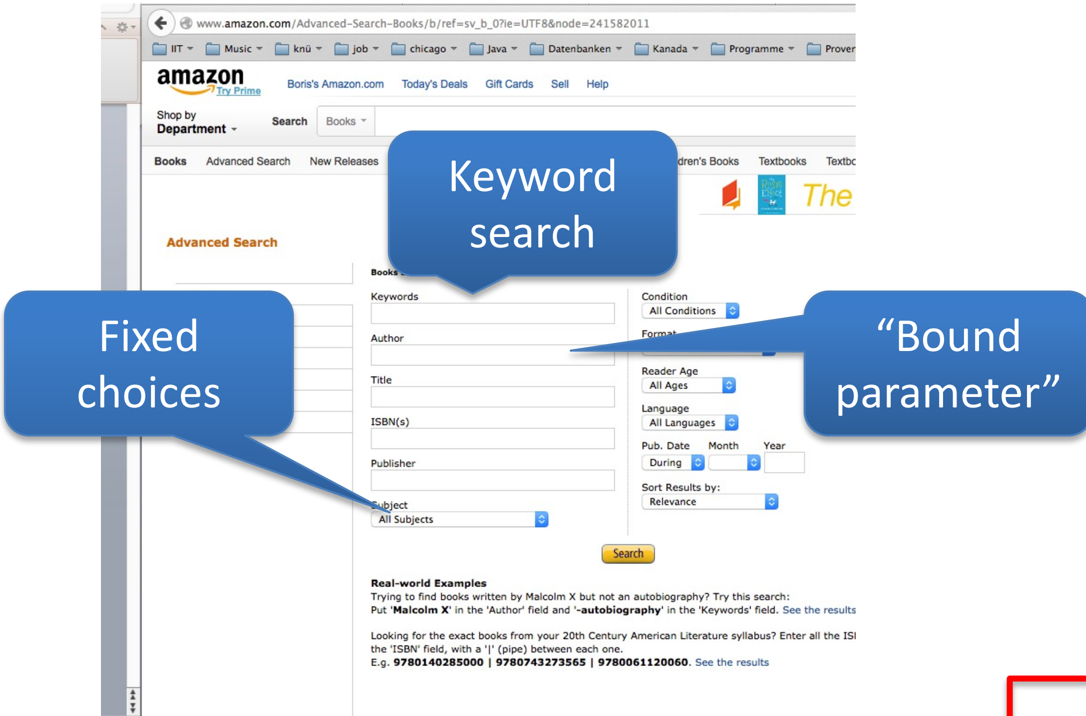


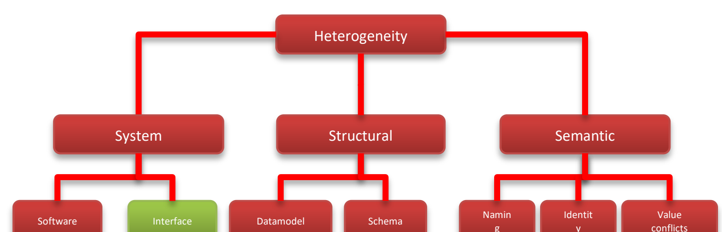
- Interface Heterogeneity – Examples
  - SQL





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





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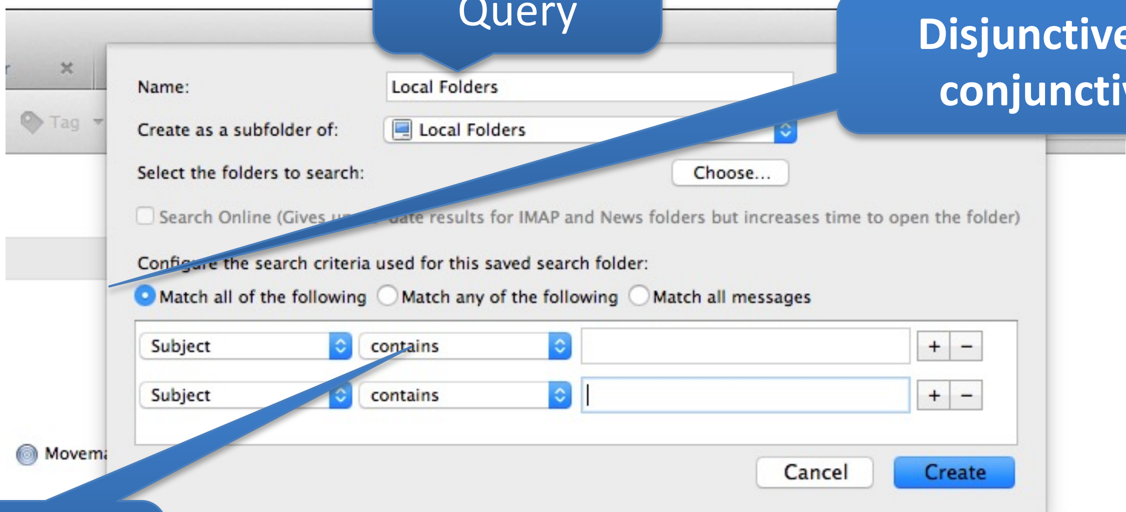
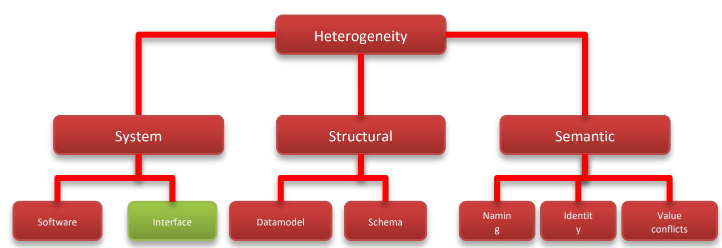
- Interface Heterogeneity – Examples
  - Email-client

Name Query

Disjunctive or conjunctive



Comparison operator



1.1 System Heterogeneity

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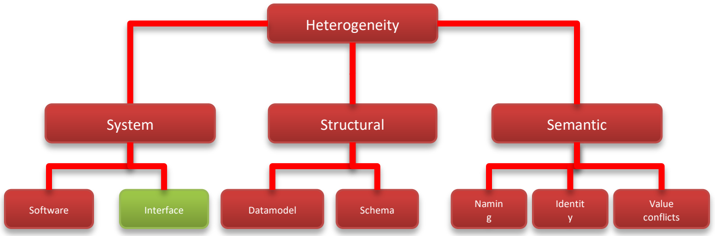
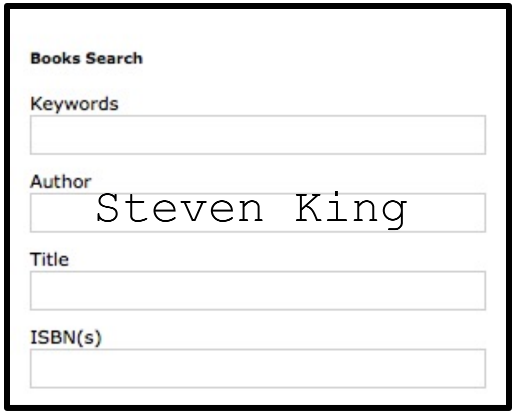
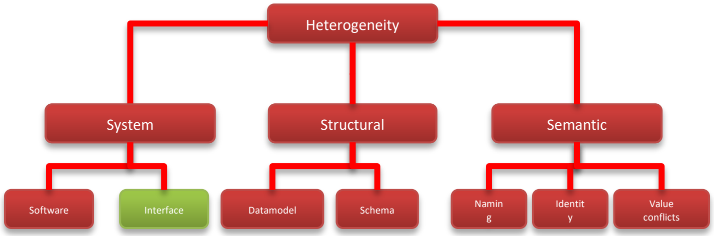
- Problems with interface heterogeneity
  - Global query language is more powerful
    - User queries may not be executable
    - Integration system has to evaluate part of the query
  - Bound parameters are incompatible with query
    - User query may not be executable



1.1 System Heterogeneity

- 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?





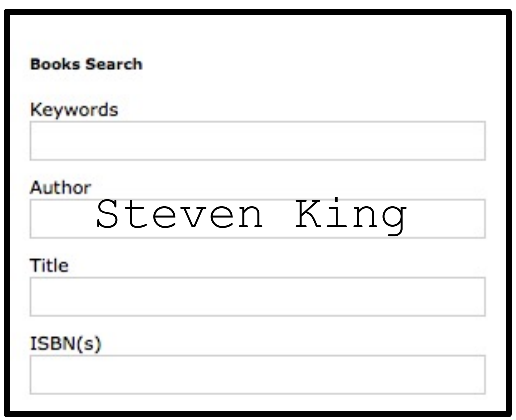
1.1 System Heterogeneity

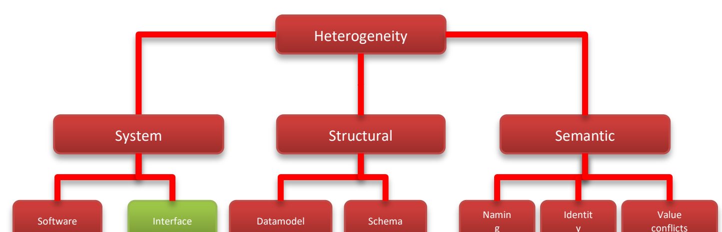
- Integration system has to process part of the query

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

Stephen King, 2012, Misery

Stephen King, 2012, Misery
Stephen King, 2014, …
Stephen Kine, 1990, …

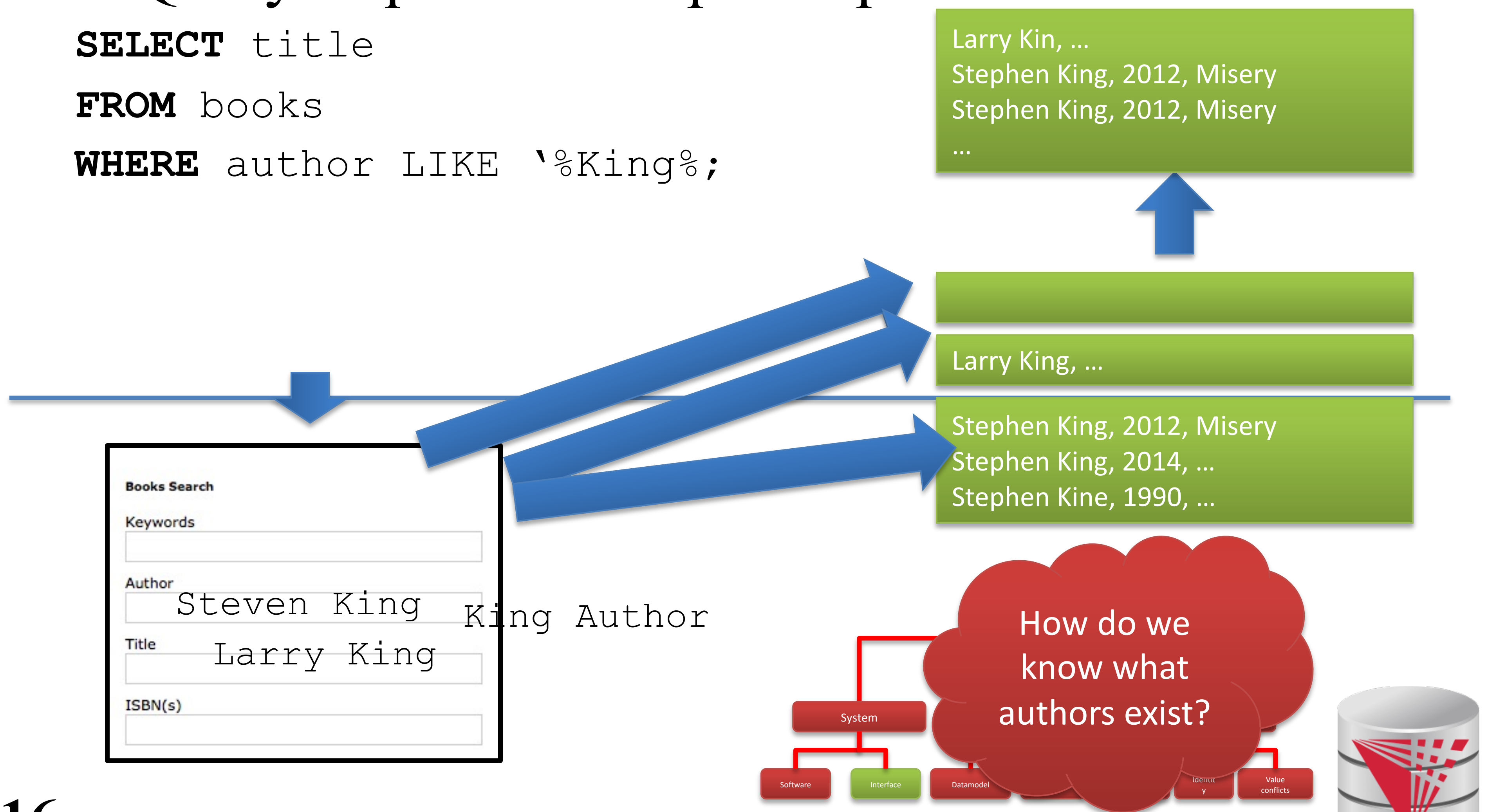




1.1 System Heterogeneity

- Query requires multiple requests

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

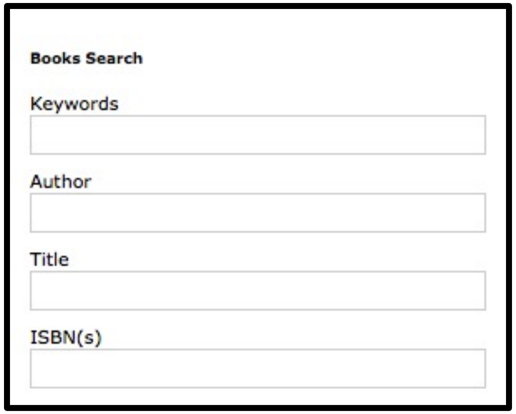


1.1 System Heterogeneity

- Query cannot be answered

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

Web form is for history book only!

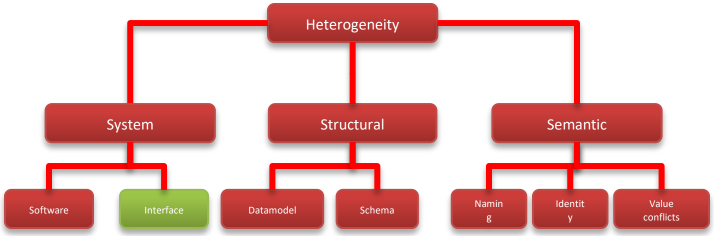

Books Search

Keywords

Author

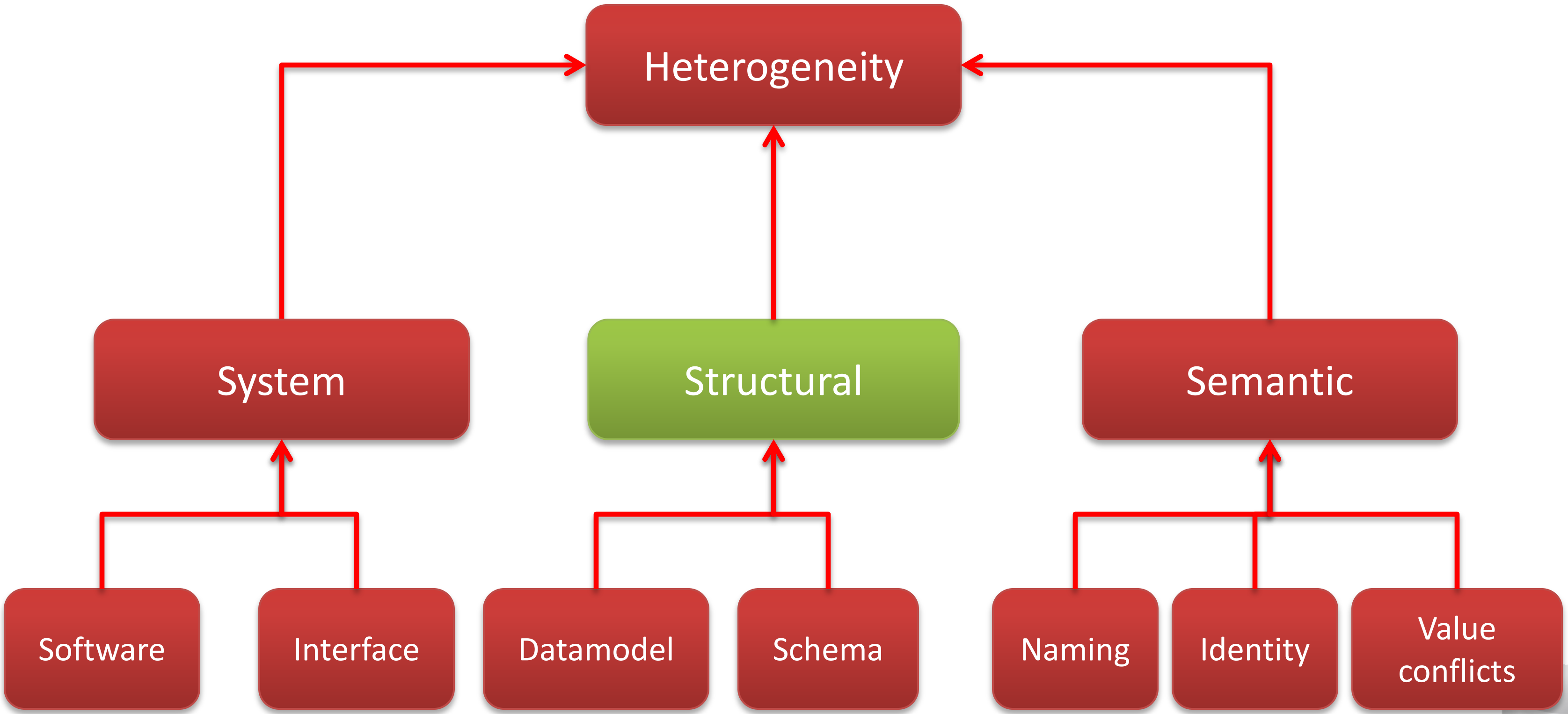
Title

ISBN(s)



1.1 Heterogeneity +Autonomy

- Taxonomy of Heterogeneity



1.1 Structural Heterogeneity

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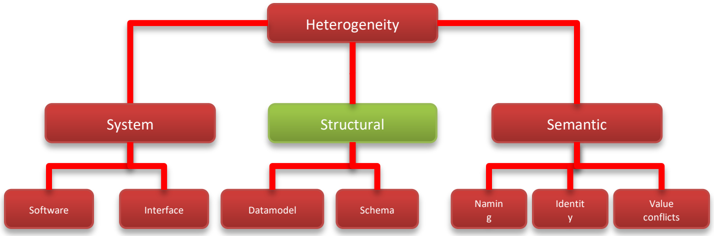
- **Data model**
  - Different semantic/expressiveness
  - Different structure
- **Schema**
  - **Integrity constraints, keys**
  - **Schema elements**:
    - use attribute or separate relations)
  - **Structure**:
    - e.g., normalized vs. denormalized relational schema



1.1 Structural Heterogeneity

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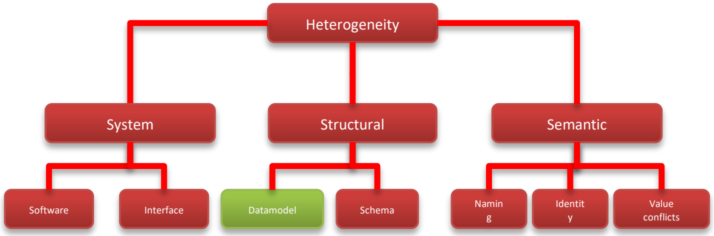
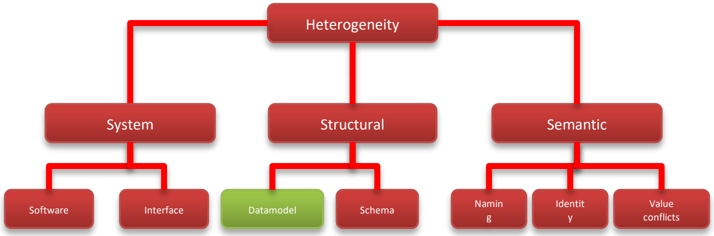
- **Data model**
  - Relational model
  - XML model
  - Object-oriented model
  - Ontological model
  - JSON
  - …



1.1 Structural Heterogeneity

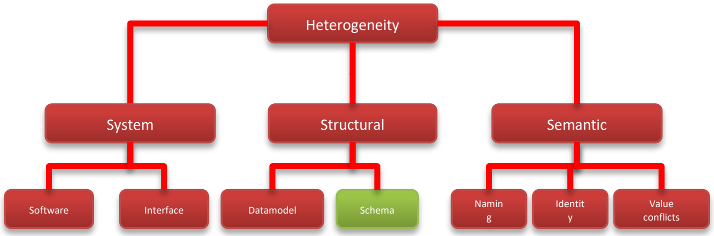
- Example: data model
  - Relational model
  - XML model
  - JSON
  - OO

- Person and their addresses



1.1 Structural Heterogeneity

- **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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Example: Modeling choices

```
Male(Id, firstname, lastname)
Female(id, firstname, lastname)
```

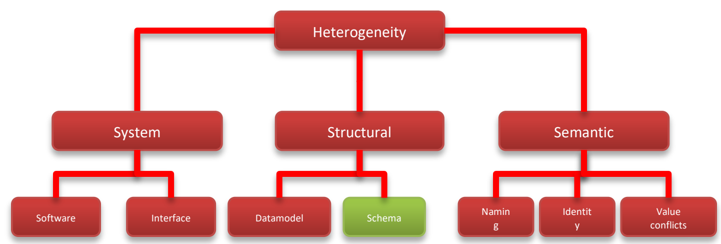
Relation vs. Attribute

Relation vs. Value

```
Person(Id, firstname, lastname, male, female)
```

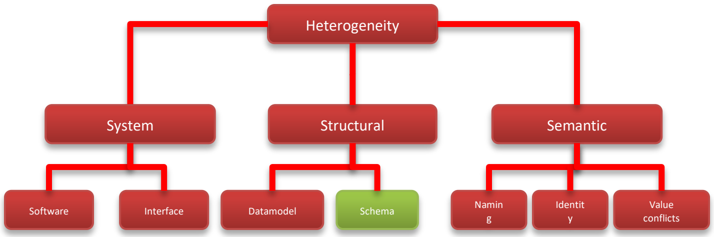
```
Person(Id, firstname, lastname, gender)
```

Value vs. Attribute



1.1 Structural Heterogeneity

- **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



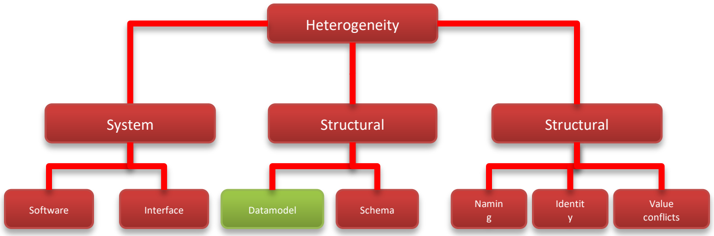
1.1 Structural Heterogeneity

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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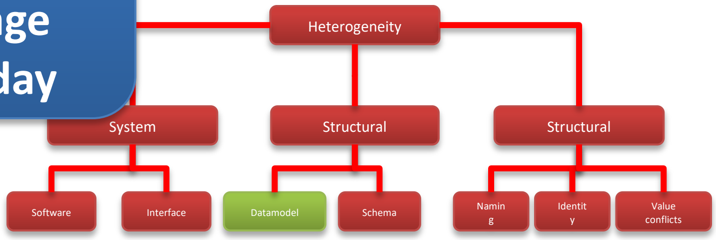
Mutliple attribtue vs one attribute

Example: Conflict between relations

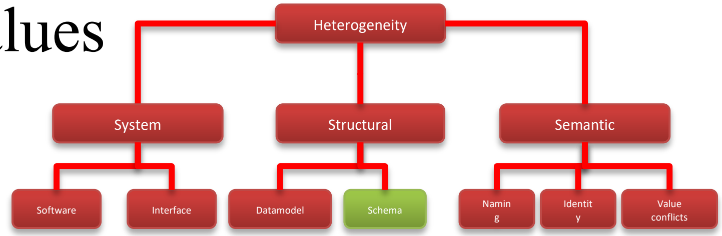
```
Person(Id, firstname, lastname, male, female)

Person(Id, name, gender, birthday)

Manager(Id, name, gender, age)
```

Missing derivable attribute: Role

Derivable attribute: Compute age from birthday



- **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

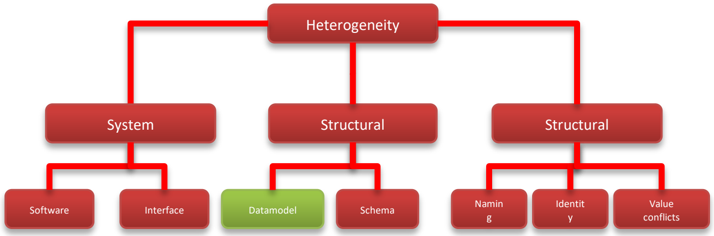


1.1 Structural Heterogeneity

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)
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

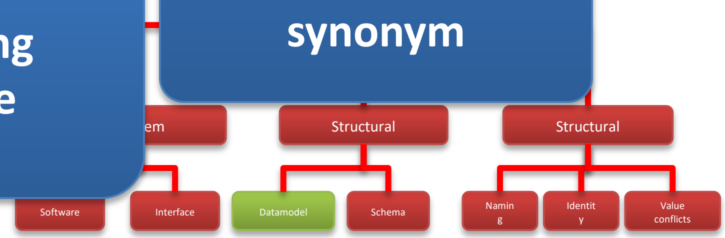
Conflicting constraint

Conflicting default value

Conflicting format

Conflicting datatype

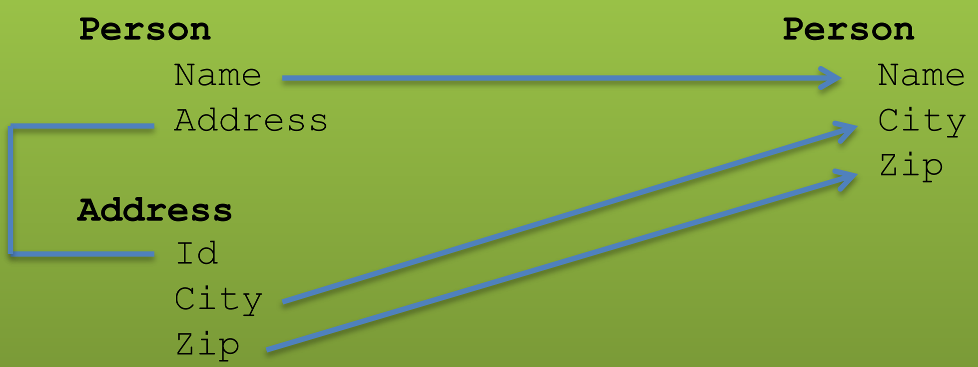
synonym

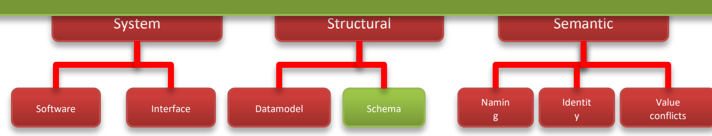


1.1 Structural Heterogeneity

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

Example

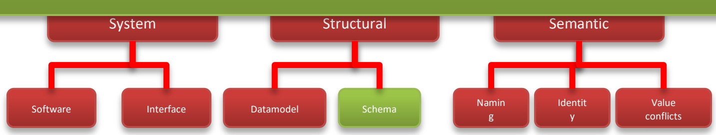




1.1 Structural Heterogeneity

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

Example



1.1 Structural Heterogeneity

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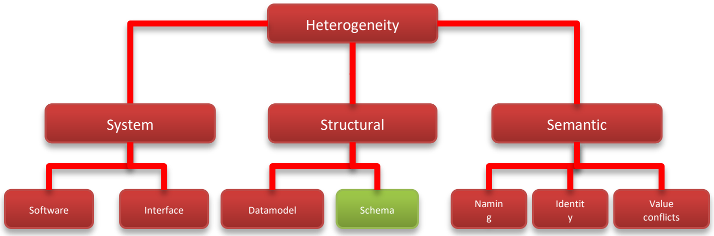
- **Problems caused by schema heterogeneity**
  - Unified access to multiple schemas or integrate schemas into new schema
    - **Schema level**: schema mapping, model management operators, schema languages
    - **Data Level:** virtual data integration, data exchange, warehousing (ETL)



1.1 Heterogeneity +Autonomy

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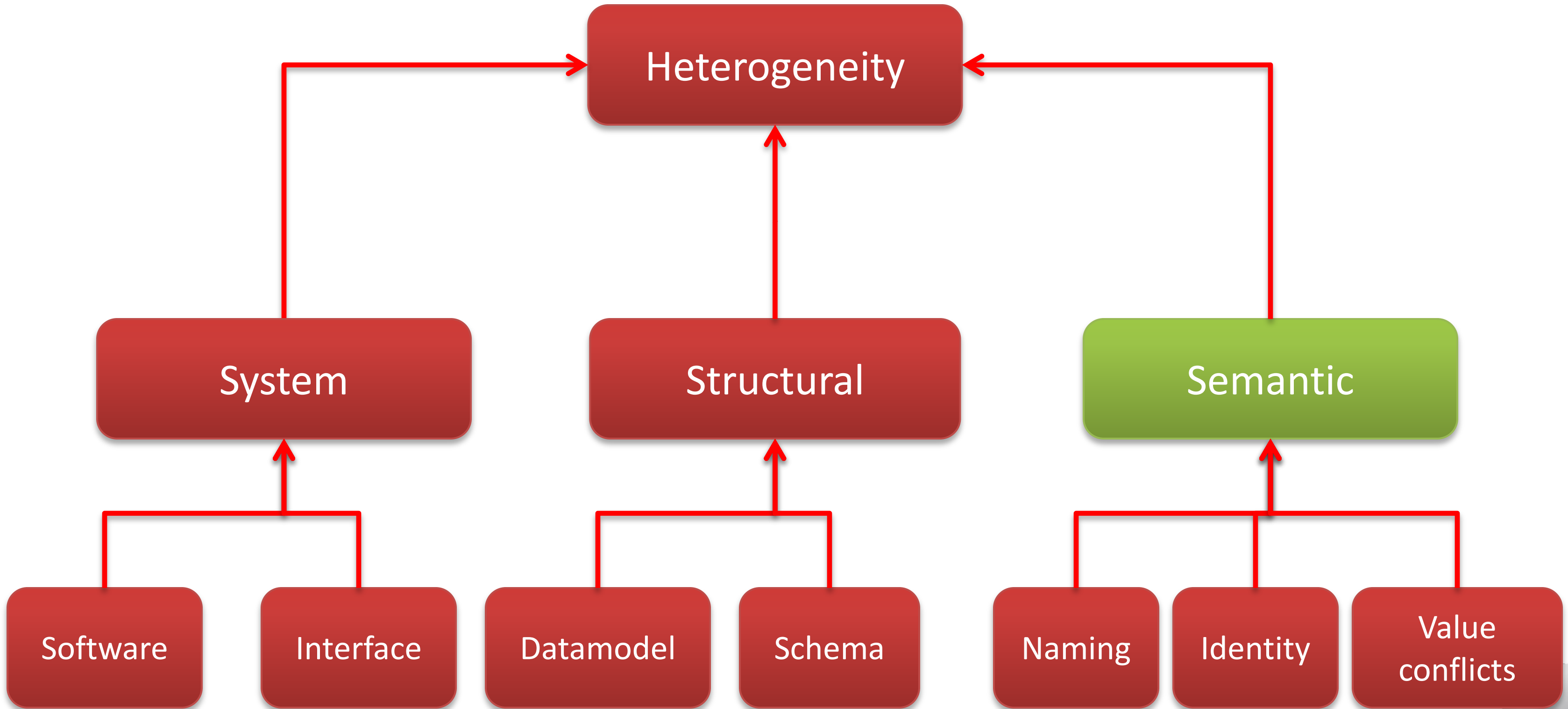
- Taxonomy of Heterogeneity



1.1 Semantic Heterogeneity

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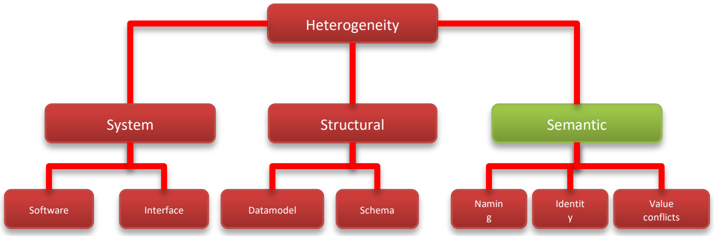
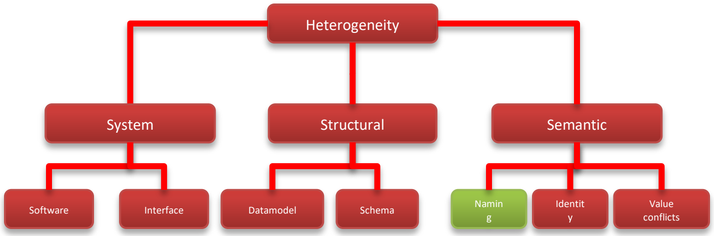
- **Semantic Heterogeneity**
  - Naming Conflicts
  - Identity Conflicts (Entity resolution)
  - Value Conflicts (Data Fusion)



1.1 Semantic Heterogeneity

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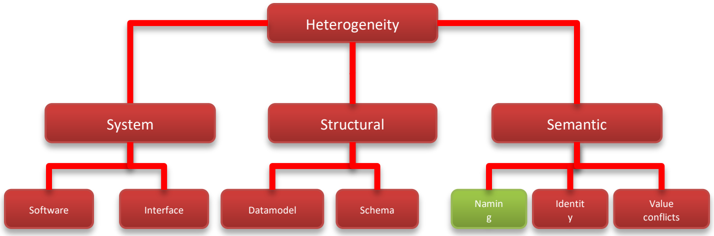
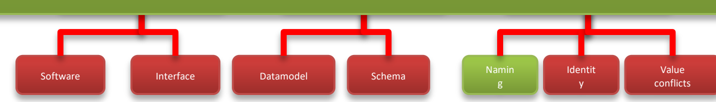
- **Ontological concepts**
  - Relationships between concepts
    - **A = B** - Equivalence
    - **A ⊆B** - Inclusion
    - **A ∩ B** - Overlap
    - **A ≠ B** - Disjunction



- **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



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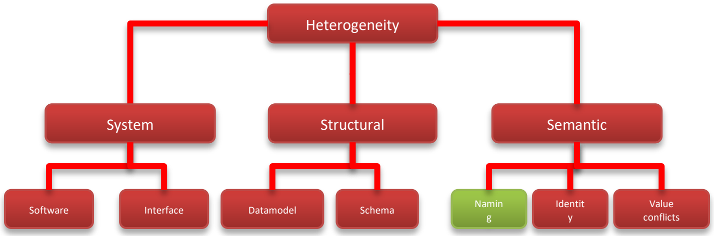
- **Naming concepts (synonyms)**
  - **Different** words with **same meaning**

Example

Person(Name, Age)

Human(LastName, Age)



1.1 Semantic Heterogeneity

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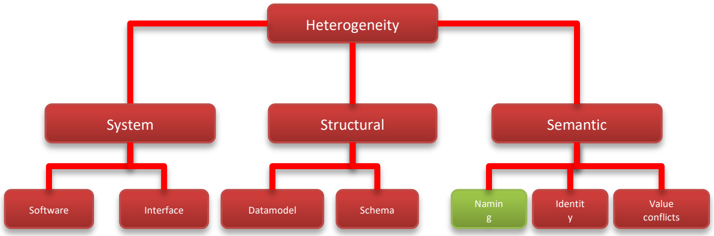
- **Naming concepts (homonyms)**
  - **Same** words with **different meaning**

Example

```
Person (Title, Name)

Movie (Title, Year)
```



1.1 Semantic Heterogeneity

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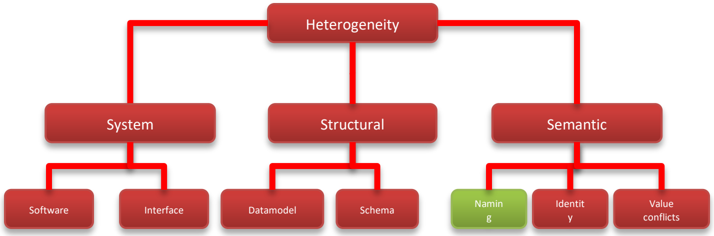
- **Naming concepts (units)**

Example

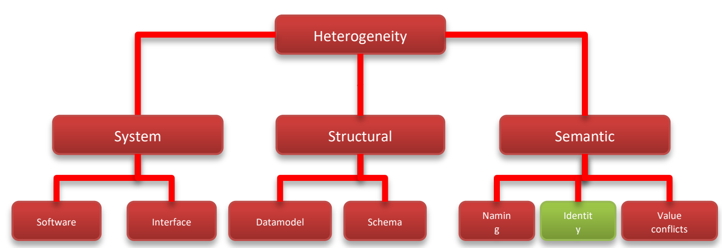
Person(Title,Name,Salary) → $

Person(Title,Name,Salary) → CAD



1.1 Semantic Heterogeneity

- 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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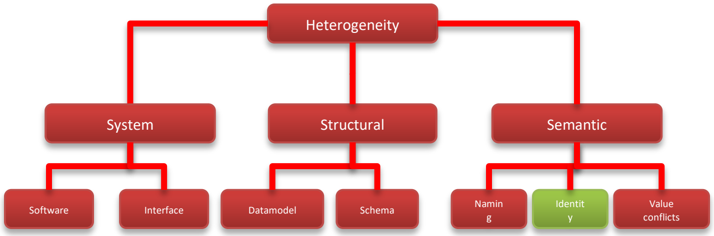
- Identity Conflicts

Example

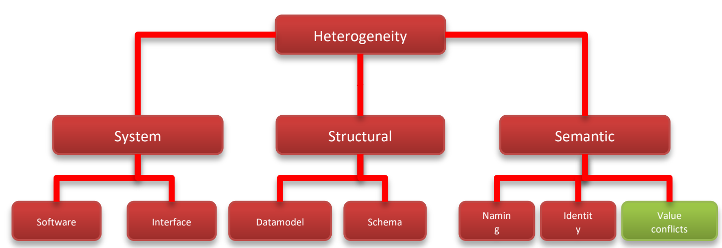
```
(IBM,300000000,USA)

(International Business Machines Corporation,50000)
```



1.1 Semantic Heterogeneity

- **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

- **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

- **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

- **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 Boolean Logic

- **Boolean Logic (syntax)**
  - **Atomic formulas:**
    - Boolean constants (**true, false)**
    - Boolean Variables (can take Boolean constants as values)
  - **Formulas:**
    - Any atomic formula is also a formula
    - If ϕ, ψ are formulas then the following are also valid formulas:

$\neg \phi$ $\qquad$ $\phi \wedge \psi$

$\phi \vee \psi$ $\qquad$ $\phi \rightarrow \psi$

1.4 Boolean Logic

- **Boolean Logic (semantics)**
  - **Valuation:**
    - Assign truth values to the variables of a formula
    - Under a valuation a formula evaluates to a Boolean value (true or false)
    - If there exists a valuation that makes the formula ψ true then the formula ψ is called **satisfiable**
  - **Semantics:**
    - Expected semantics of Boolean operators:

$$\top \wedge \bot = \bot$$
$$\top \wedge \top = \top$$
$$\bot \vee \top = \top$$
$$\ldots$$

1.4 Boolean Logic

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Example

Formula:

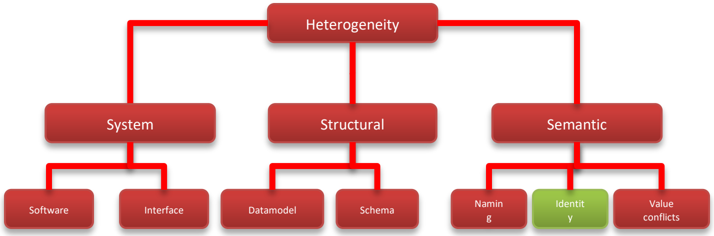
$$(x \vee y) \wedge \neg z$$

A possible valuation:

$$\nu : x = \top, y = \bot, z = \top$$

Evaluating the formula:

$$(\top \vee \bot) \wedge \neg \top = \top \wedge \bot = \bot$$



1.4 First-order logic (FO)

– Concepts

- **Domain of discourse** $\mathbb{D}$
  - These are the values that we can bind variables to
  - Values from the domain can also be used as constants in formulas
- **A set of predicate symbols (each with an arity)**

$$R_1, \ldots, R_n$$

  - These represent relations (in the mathematical sense)
- **An infinite set of variables** $\mathcal{X}$

1.4 FO Syntax

- **Terms**
  - **Variables:** any variable from $\mathcal{X}$ is a term
  - **Constants:** any constant from $\mathbb{D}$ is a term
- **Atomic formulas:**
  - For any n-ary predicate *R* and terms $t_1, \ldots, t_n$ $R(t_1, \ldots, t_n)$ is an atomic formula
- **Formulas:**
  - If ϕ, ψ are formulas then the following are also valid formulas:

$\psi \wedge \phi$ $\psi \vee \phi$ $\neg \phi$

$\psi \rightarrow \phi$ $\exists x : \psi$ $\forall x : \psi$

1.4 Free / Bound Variables

– Free variables of a formula

- All variables not bound by quantifiers

$$free(\neg\psi) = free(\psi)$$
$$free(\psi \wedge \phi) = free(\psi) \cup free(\phi)$$
$$free(\psi \vee \phi) = free(\psi) \cup free(\phi)$$
$$free(\forall x : \psi) = free(\psi) - \{x\}$$
$$free(\exists x : \psi) = free(\psi) - \{x\}$$
$$free(R(t_1, \ldots, t_n)) = free(t_1) \cup \ldots \cup free(t_n)$$
$$free(x) = \{x\}$$
$$free(c) = \emptyset$$

1.4 FO Semantics

- **Model** $\mathcal{M}$
  - an interpretation of the predicates, i.e., we assign each predicate to a concrete relation
  - We select a domain of discourse $\mathbb{D}$
- **Valuations** μ **for a formula** ψ
  - Assigns free variables of ψ to values from $\mathbb{D}$
- **Substitutions**
  - Replace all free occurrences of variable x with c

$$\psi[x \leftarrow c]$$

1.4 FO Semantics

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- **Given a model $\mathcal{M}$ and valuation μ**
  - The "result" of a formula $[\![\psi]\!]_{\mathcal{M},\mu}$

$$[\![c]\!]_{\mathcal{M},\mu} = c$$

$$[\![x]\!]_{\mathcal{M},\mu} = \mu(x)$$

$$[\![R(t_1,\ldots,t_n)]\!]_{\mathcal{M},\mu} = \begin{cases} \top & \text{if } ([\![t_1]\!]_{\mathcal{M},\mu},\ldots,[\![t_n]\!]_{\mathcal{M},\mu}) \in R \\ \bot & \text{otherwise} \end{cases}$$

$$[\![\psi \wedge \phi]\!]_{\mathcal{M},\mu} = [\![\psi]\!]_{\mathcal{M},\mu} \wedge [\![\phi]\!]_{\mathcal{M},\mu}$$

$$[\![\psi \vee \phi]\!]_{\mathcal{M},\mu} = [\![\psi]\!]_{\mathcal{M},\mu} \vee [\![\phi]\!]_{\mathcal{M},\mu}$$

$$[\![\neg\,\psi]\!]_{\mathcal{M},\mu} = \neg\,[\![\psi]\!]_{\mathcal{M},\mu}$$

$$[\![\exists x : \psi]\!]_{\mathcal{M},\mu} = \bigvee_{c \in \mathbb{D}} : [\![\psi[x \leftarrow c]]\!]_{\mathcal{M},\mu}$$

$$[\![\forall x : \psi]\!]_{\mathcal{M},\mu} = \bigwedge_{c \in \mathbb{D}} : [\![\psi[x \leftarrow c]]\!]_{\mathcal{M},\mu}$$

Example

Formula: $\psi = \forall y : R(x, y)$

Model: $\mathcal{M} = \{R = \{(1,1), (1,2), (1,3)\}$

$\mathbb{D} = \{1, 2, 3\}\}$

Valuation: $\mu(x) = 1$

Result:

$$
\begin{aligned}
&[\![\forall y : R(x, y)]\!]_{\mathcal{M},\mu} \\
=&[\![R(x, 1)]\!]_{\mathcal{M},\mu} \wedge [\![R(x, 2)]\!]_{\mathcal{M},\mu} \wedge [\![R(x, 3)]\!]_{\mathcal{M},\mu} \\
=&[\![(x, 1)]\!]_{\mathcal{M},\mu} \in R \wedge [\![(x, 2)]\!]_{\mathcal{M},\mu} \in R \wedge [\![(x, 3)]\!]_{\mathcal{M},\mu} \in R \\
=&(\mu(x), 1) \in R \wedge (\mu(x), 2) \in R \wedge (\mu(x), 3) \in R \\
=&(1, 1) \in R \wedge (1, 2) \in R \wedge (1, 3) \in R \\
=&\top \wedge \top \wedge \top \\
=&\top
\end{aligned}
$$

1.4 FO Problems

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- **Model checking**
  - Given a model $\mathcal{M}$ and formula ψ without free variables
  - Is $[\![\psi]\!]_{\mathcal{M},\mu}$ true?
- **Satisfiability**
  - Given a formula ψ does there exist a model $\mathcal{M}$ and valuation μ such that $[\![\psi]\!]_{\mathcal{M},\mu}$ is true?

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

- 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

Example

Primary Key R(<u>A</u>,B):

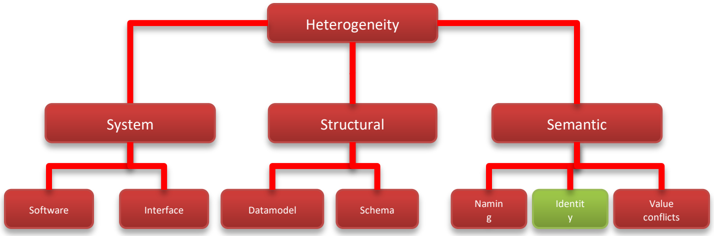
$$\forall x, y, z : R(x,y) \wedge R(x,z) \rightarrow y = z$$

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(<u>A</u>,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

- 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

- 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**

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

- **Procedural Interpretation:** For all bindings of variables 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

- 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

- 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

- **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

- 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

Example

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

N
peter
bob

```
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).
```

Active domain

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

Name	Age
peter	34
bob	34

1.4 Datalog

- 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

- Different flavors of datalog
  - **Recursion**
    - Rules may have recursion:
      - E.g., head predicate in the body
    - Fixpoint 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=bob,A=34: Q(bob):- Person(bob,34),
not Lives(bob).

...

Active domain

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

Result

N
bob

Lives

Name
peter

Person

Name	Age
peter	34
bob	34

1.4 Datalog

Example

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

$Q_{2hop}(x,z)$: hop(x,y),hop(y,z).

$Q_{reach}(x,y)$: hop(x,y).
$Q_{reach}(x,z)$: $Q_{reach}(x,y)$,$Q_{reach}(y,z)$.

$Q_{node}(x)$: hop(x,y).
$Q_{node}(x)$: hop(y,x).

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Example

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

Q_{node}(x): hop(x,y).
Q_{node}(x): hop(y,x).

$Q_{notReach}$(x,y): Q_{node}(x), Q_{node}(y),
not Q_{reach}(x,y).

1.4 Datalog versus FO

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- A Datalog rule is a FO implication:

$$Q(X, Y) :- R(X, Z), R(Z, Y).$$

Means

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

- Databases can be expressed as rules!

$$R = \{(Peter, Bob), (Bob, Alice)\}$$

$$R(Peter, Bob) :-$$

$$R(Bob, Alice) :-$$

1.4 Model-theoretic semantics

- The result of a Datalog program P is the smallest model $\mathcal{M}$ for the program if interpreted as a logical formula
  - Only facts that are justified by the program are included in the query result!

1.4 Free Datalog Systems

- Datalog Education System (DES)
  - http://des.sourceforge.net/
- DLV
  - http://www.dlvsystem.com/dlv/

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

- 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

Q_1(x,y): R(x,y), R(x,z).
Q_2(x,y): R(x,y).
Q_3(x,x): R(x,x).
Q_4(x,y): R(x,y).
Q_5(x,x): R(x,y), R(x,x).
Q_6(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.

Q_{2hop}(x,z): hop(x,y),hop(x,z).

Q_{up2Hop}(x,z): hop(x,y),hop(x,z).
Q_{up2Hop}(x,z): hop(x,z).

Q_{sym}(x,y): hop(x,y).
Q_{sym}(x,y): hop(y,x).
$Q_{sym2Hop}$(x,y): Q_{sym}(x,y),Q_{sym}(y,z).

1.4 Complexity of Eq. and Cont.

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	Π_2^p-complete
Query Containment	Undecidable	NP-complete	NP-complete	Π_2^p-complete

1.4 Complexity of Eq. and Cont.

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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

- 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

- 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

- 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
```

- 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

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

Example

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

Can we find a containment mapping?

1.4 Containment Mappings

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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

$Q_1(u,z)$: R(u,z).
$Q_2(x,y)$: R(x,y).

$Q_1 \rightarrow Q_2 : \Psi(u)=x, \Psi(z)=y$
$Q_2 \rightarrow Q_1 : \Psi(x)=u, \Psi(y)=z$

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Example

Q_1(a,b): R(a,b), R(b,c).

Q_2(x,y): R(x,y).

1.4 Containment Mappings

Example

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

Do containment mappings exist?

Q_1 -> Q_2: none exists
Q_2 -> Q_1: Ψ(x)=a, Ψ(y)=b

1.4 Containment Mappings

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

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- 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

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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

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

- 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

- 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

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

- **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

- **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

- **Interpretation: the lower the score the "more similar" the objects are**
- **We require d(p,p)=0, because nothing can be more similar to an object than itself**
- **Note: often scores are normalized to the range [0,1]**

1.4 Similarity Measures

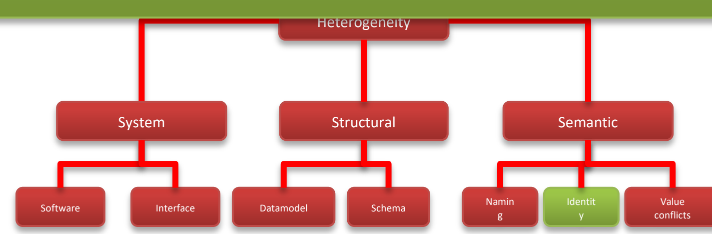
Example

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

Euclidian distance: d(p,q) =
N-dimensional space

$$d(p,q) = \sqrt{\sum_{i=1}^{n} (p[i] - q[i])^2}$$

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



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

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1.4 Similarity Measures

- **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

- 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

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