Ontologies in data integration

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Technologies for Information Systems

The new application context (recall)

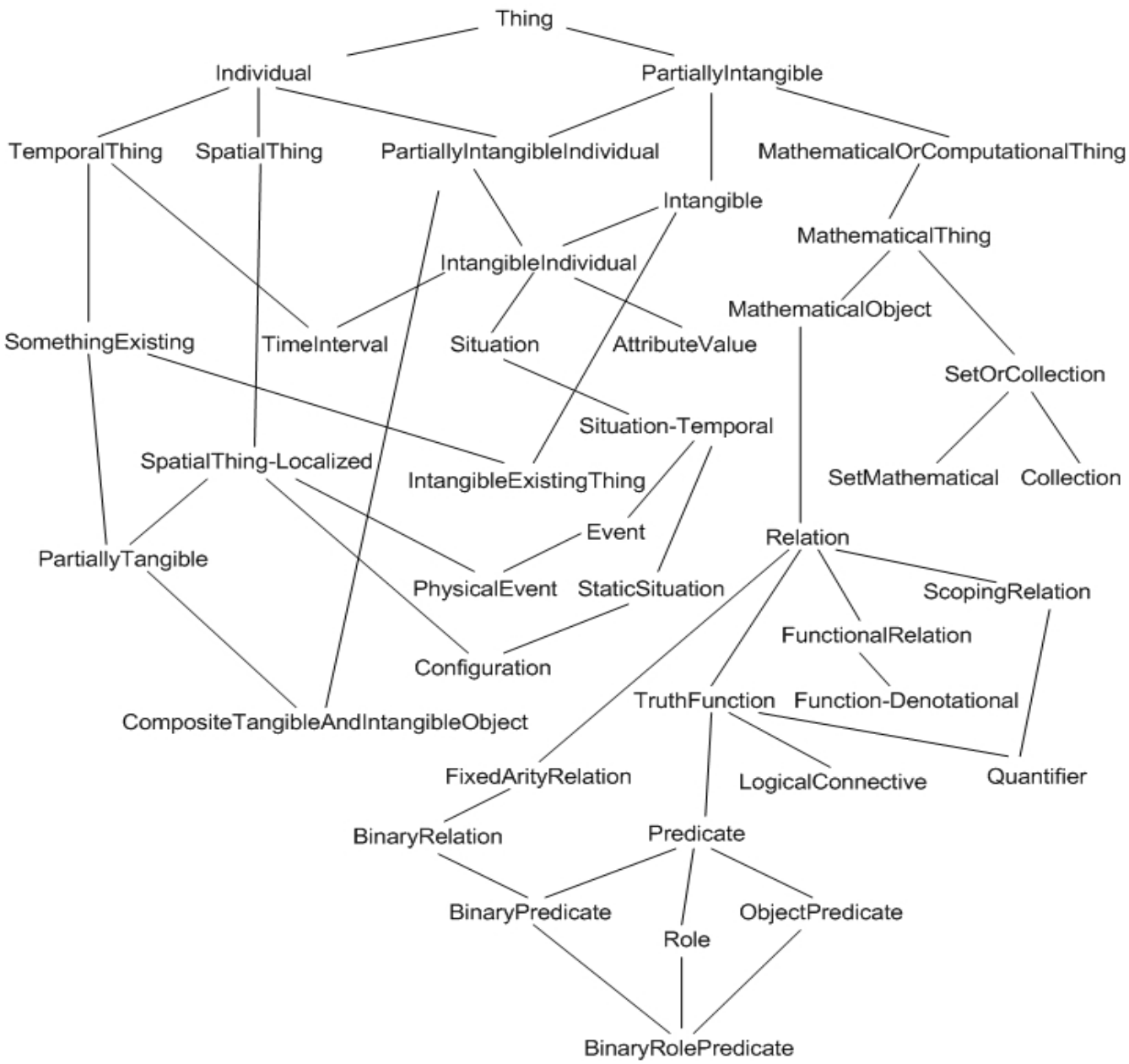
- A (possibly large) number of data sources
- Time-variant data (e.g. WEB)
- Heterogeneous data sources
- Mobile, transient data sources
- Different levels of data structure
  - Databases (relational, OO…)
  - Semi-structured data sources (XML, HTML, more markups …)
  - Unstructured data (text, multimedia etc…)
- Different terminologies and different operational contexts

Ontologies

- A formal and shared definition of a vocabulary of terms and their inter-relationships
- Predefined relations:
  - *synonimy*
  - *omonimy*
  - *hyponimy*
  - *etc..*
- More complex, designer-defined relationships, whose semantics depends on the domain

  →e.g. enrolled(*student,course)*

→ an ER diagram, a class diagram, any conceptual schema *is an ontology!*


Thing
Individual
PartiallyIntangible
TemporalThing
SpatialThing
PartiallyIntangibleIndividual
MathematicalOrComputationalThing
Intangible
MathematicalThing
IntangibleIndividual
MathematicalObject
SomethingExisting
TimeInterval
Situation
AttributeValue
SetOrCollection
Situation-Temporal
SpatialThing-Localized
IntangibleExistingThing
SetMathematical
Collection
Event
Relation
PartiallyTangible
PhysicalEvent
StaticSituation
ScopingRelation
FunctionalRelation
Configuration
TruthFunction
Function-Denotational
CompositeTangibleAndIntangibleObject
FixedArityRelation
LogicalConnective
Quantifier
BinaryRelation
Predicate
BinaryPredicate
ObjectPredicate
Role
BinaryRolePredicate

A philosophical concept…

- Introduced by Aristoteles
- The science of being, i.e. the science of *what is*
- Ontology, as a philosophical discipline, studies the answers to questions like:
  - ***What does "being" mean?***
  - ***What are the features common to all beings?***

Definitions

- Ontology = formal specification of a conceptualization of a shared knowledge domain.
- An ontology is a controlled vocabulary that describes objects and the relationships between them in a formal way
- It has a grammar for using the terms to express something meaningful within a specified domain of interest.
- The vocabulary is used to express queries and assertions.
- Ontological commitments are agreements to use the vocabulary in a consistent way for knowledge sharing

semantic interoperability → semantic Web

Aims…

- A formal specification allows for use of a common vocabulary for *automatic knowledge sharing*
- Formally specifying a *conceptualization* means giving a unique meaning to the terms that define the knowledge about a given domain
- *Shared:* an ontology captures knowledge which is common, thus *over which there is a consensus* (objectivity is not an issue here)

Ontology types

- **Taxonomic ontologies**
  - Definition of concepts through terms, their hierarchical organization, and additional (pre-defined) relationships (synonymy,composition,…)
  - To provide a reference vocabulary
- **Descriptive ontologies**
  - Definition of concepts through data structures and their interrelationships
  - Provide information for “aligning” existing data structures or to design new, specialized ontologies (***domain ontologies***)
  - Closer to the database area techniques

Wordnet

horse, Equus caballus:
a solid-hoofed
herbivorous quadruped
domesticated since
prehistoric times

WordNet

- entity, physical thing
  - object, physical object
    - living thing, animate thing
      - organism, being
        - animal, animate being, beast, brute, creature, fauna
          - chordate
            - vertebrate, craniate
              - mammal
                - placental, placental mammal, eutherian, eutherian mammal
                - ungulate, hoofed mammal
                - odd-toed ungulate, perissodactyl, perissodactyl mammal
                - equine, equid
                - horse, Equus caballus
                - saddle horse, riding horse, mount
                - Arabian, Arab

An ontology consists of…

- Concepts:
  - Generic concepts, they express general world categories
  - Specific concepts, they describe a particular application domain (***domain ontologies***)
- Concept Definition
  - Via a formal language
  - In natural language
- Relationships between concepts:
  - Taxonomies (IS_A),
  - Meronymies (PART_OF),
  - Synonymies, homonymies, ...
  - User-defined associations,

Formal Definitions

O = (C, R, I, A)

O ontology, *C* concepts, *R* relations, *A* axioms

- Specified in some logic-based language
- Organized in a ISA hierarchy
- *I*= instance collection, stored in the information source
- Composed by a *T-Box* (theory) and an *A-box* (instances)

Formal Definitions

An ontology is (part of) a knowledge base, composed by:

- a ***T-Box****:* contains all the concept and role definitions, and also contains all the axioms of our logical theory (e.g. “A father is a Man with a Child”).
- an ***A-box***: contains all the basic assertions (also known as ground facts) of the logical theory (e.g. “Tom is a father” is represented as Father(Tom)).

OpenCyc

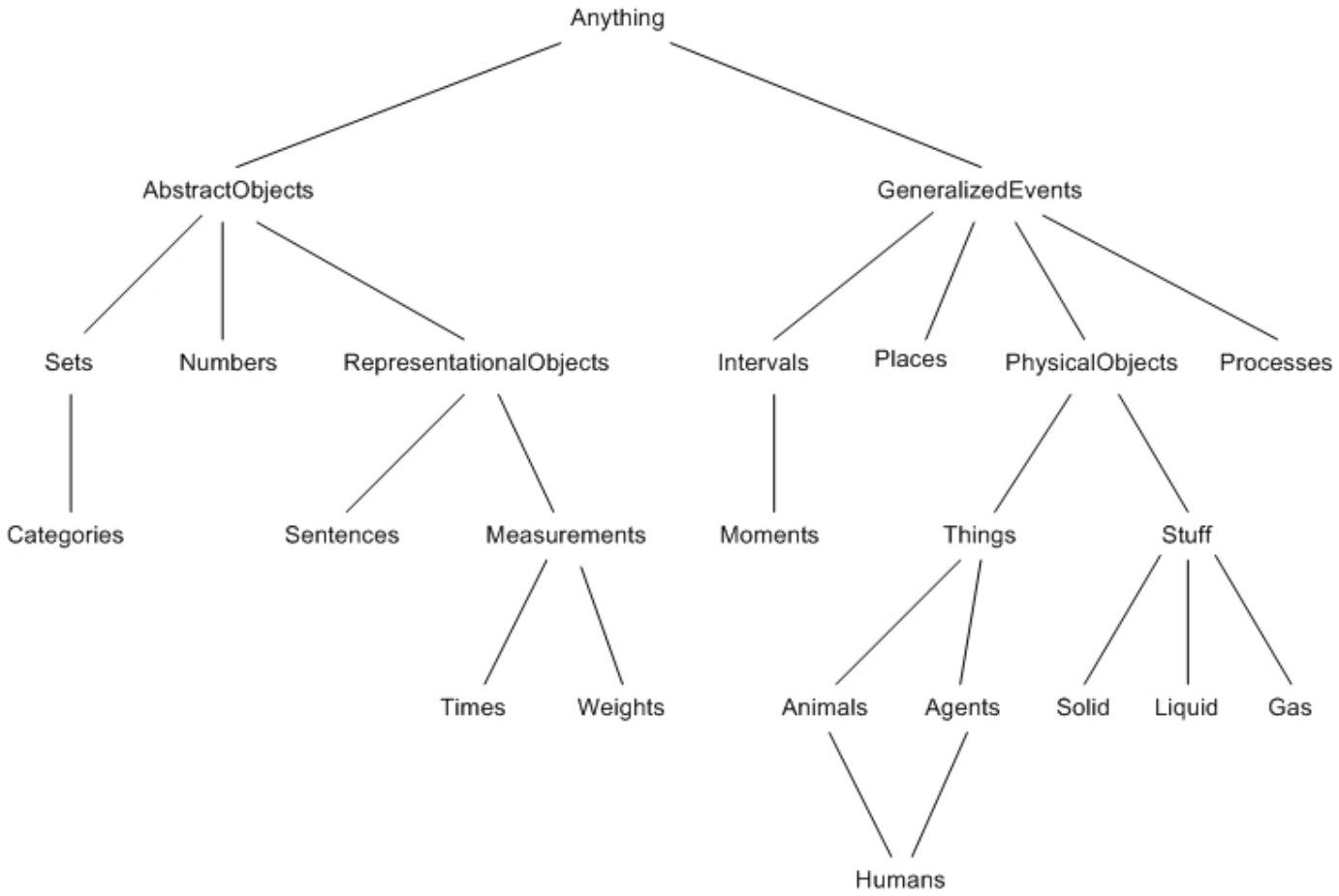
- The open source version of the Cyc technology
- The entire Cyc ontology containing hundreds of thousands of terms, along with millions of assertions relating the terms to each other, forming an ontology whose domain is all of human consensus reality.
- The Cyc project was born in 1984 and is still continuing http://www.cyc.com/opencyc
- Available for downoad from SourceForge

Release 2.0 of OpenCyc

- 100,000+ "broaderTerm" assertions, in addition to the previous generalization (subclass) and instance (member) assertions, to capture additional relations among concepts.
- English strings (a canonical one and alternatives) corresponding to each concept term, to assist with search and display.
- The Cyc Inference Engine and the Cyc Knowledge Base Browser are now Java-based for improved performance and increased platform portability.
- Documentation and self-paced learning materials to help users achieve a basic- to intermediate-level understanding of the issues of knowledge representation and application development using Cyc.
- A specification of CycL, the language in which Cyc (and hence OpenCyc) is written.
- A specification of the Cyc API for application development.
- Links between Cyc concepts and WordNet synsets.
- Links between Cyc concepts (including predicates) and the FOAF ontology http://xmlns.com/foaf/spec/20100809.html#term_Agent
- Links between Cyc concepts and Wikipedia articles

Top level concepts of Cyc

Top level concepts of the Russel and Norvig ontology



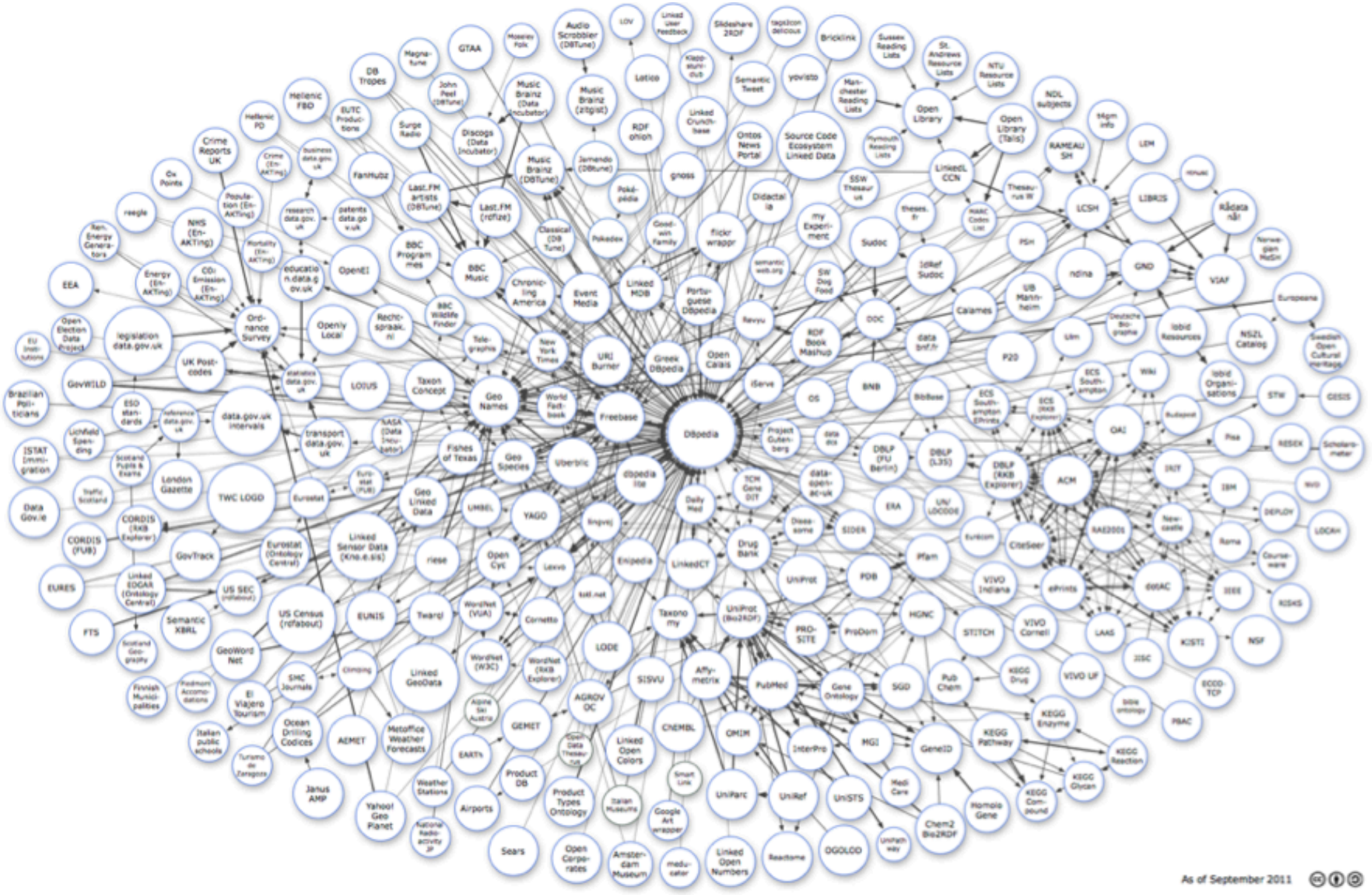
The Semantic Web

- a vision for the future of the Web in which information is given explicit meaning, making it easier for machines to automatically process and integrate information available on the Web.
- will build on XML's ability to define customized tagging schemes and RDF's flexible approach to representing data.
- The first level above RDF: OWL, an ontology language what can formally describe the meaning of terminology used in Web documents → beyond the basic semantics of RDF Schema.

A fragment of an RDF (XML) document, describing an ontology.
The language is OWL
http://www.w3.org/TR/owl-ref/

```
<?xml version="1.0"?>
<rdf:RDF
    xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
    xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
    xmlns:owl="http://www.w3.org/2002/07/owl#"
    xmlns:daml="http://www.daml.org/2001/03/daml+oil#"
    xmlns="http://eng.it/ontology/tourism#"
    xmlns:dc="http://purl.org/dc/elements/1.1/"
  xml:base="http://eng.it/ontology/tourism">
  <owl:Ontology rdf:about=""/>
  <owl:Class rdf:ID="Church">
    <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
    >Definition: Edificio sacro in cui si svolgono pubblicamente gli atti
di culto delle religioni cristiane.</rdfs:comment>
    <rdfs:subClassOf>
      <owl:Class rdf:about="#PlaceOfWorship"/>
    </rdfs:subClassOf>
  </owl:Class>
  <owl:Class rdf:ID="Theatre">
    <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
    >Definition: a building where theatrical performances or motion-
picture shows can be presented.</rdfs:comment>
    <rdfs:subClassOf>
      <owl:Class rdf:about="#SocialAttraction"/>
    </rdfs:subClassOf>
  </owl:Class>
  <owl:Class rdf:ID="DailyCityTransportationTicket">
    <rdfs:subClassOf>
      <owl:Class rdf:about="#CityTransportationTicket"/>
    </rdfs:subClassOf>
    <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
    >Definition: Biglietto che consente di usufruire di un numero
illimitato di viaggi sui mezzi pubblici (autobus e metropolitana)
all'interno del centro urbano (o della regione, con un costo maggiore) per
un periodo di 24 ore.</rdfs:comment>
  </owl:Class>
```

Linked Open Data Cloud Diagram



Linked Data

- Linked Data is a W3C-backed movement about connecting data sets across the Web. It describes a method of publishing structured data so that it can be interlinked and become more useful.
- It builds upon standard Web technologies such as HTTP, RDF and URIs, but extends them to share information in a way that can be read automatically by computers, enabling data from different sources to be connected and queried.
- A subset of the wider Semantic Web movement, which is about adding meaning to the Web
- Open Data describes data that has been uploaded to the Web and is accessible to all
- Linked Open Data: extend the Web with a data commons by publishing various open datasets as RDF on the Web and by setting RDF links among them

Most famous datasets

- CKAN – registry of open data and content packages provided by the Open Knowledge Foundation
- DBpedia – a dataset containing extracted data from Wikipedia; it contains about 3.4 million concepts described by 1 billion triples, including abstracts in 11 different languages
- GeoNames provides RDF descriptions of more than 7,500,000 geographical features worldwide.
- UMBEL – a lightweight reference structure of 20,000 subject concept classes and their relationships derived from OpenCyc, which can act as binding classes to external data; also has links to 1.5 million named entities from DBpedia and YAGO
- FOAF – a dataset describing persons, their properties and relationships

RDF and OWL

- Designed to meet the need for a Web Ontology Language, OWL is part of the growing stack of W3C recommendations related to the Semantic Web.
- XML provides a surface syntax for structured documents, but imposes no semantic constraints on the meaning of these documents.
- XML Schema is a language for restricting the structure of XML documents and also extends XML with data types.
- RDF is a data model for objects ("resources") and relations between them, provides a simple semantics for this data model, and can be represented in an XML syntax.
- RDF Schema is a vocabulary for describing properties and classes of RDF resources, with a semantics for generalization-hierarchies of such properties and classes.
- OWL adds more vocabulary for describing properties and classes: among others, relations between classes (e.g. disjointness), cardinality (e.g. "exactly one"), equality, richer typing of properties, characteristics of properties (e.g. symmetry), and enumerated classes.

OWL

- The OWL Web Ontology Language is designed for use by applications that need to process the content of information instead of just *presenting* information to humans.
- OWL facilitates greater machine interpretability of Web content than that supported by XML, RDF, and RDF Schema (RDF-S) by providing additional vocabulary along with a formal semantics.
- OWL has three increasingly-expressive sublanguages: OWL Lite, OWL DL, and OWL Full.

OWL SUBLANGUAGES:
OWL Lite

Supports users primarily needing a classification hierarchy and simple constraints.

- Cardinality constraints: it only permits cardinality values of 0 or 1.
- Has a lower formal complexity than OWL DL
- It is simpler to provide tool support for OWL Lite than for its more expressive relatives
- OWL Lite provides a quick migration path for thesauri and other taxonomies.

OWL SUBLANGUAGES:
OWL DL

*S*upports users who want maximum expressiveness while:

- all conclusions are guaranteed to be computable (**computational completeness**)
- all computations will finish in finite time (**decidability**)
- includes all OWL language constructs, but they can be used only under certain restrictions
  - for example, while a class may be a subclass of many classes, **a class cannot be an instance of another class**
  - so named due to its correspondence with ***Description Logics***, the logics that constitute the formal foundation of OWL.

OWL SUBLANGUAGES: *OWL FULL*

Meant for users who want maximum expressiveness and the syntactic freedom of RDF

- no computational guarantees
  - For example, in OWL Full a class can be treated simultaneously as a collection of individuals and as an individual in its own right.
- OWL Full allows an ontology to augment the meaning of the pre-defined (RDF or OWL) vocabulary
- unlikely that any reasoning software will be able to support complete reasoning for every feature of OWL Full.

Further existing projects

- **RACER :** a description logic reasoning system which implements the SHIQ Logic.
- **KAON :** an ontology and semantic web framework allowing the design and management of ontologies
- **DOGMA :** an ontology engineering framework based on the ORM (Object-Role-Modeling) conceptual model
- **MADS :** a spatio-temporal conceptual model (complex objects, n-ary relationships with attributes, generalization hierarchies, spatio/temporal and contextual features)

References

- **RACER:** http://www.sts.tu-harburg.de/~r.f.moeller/racer/
- **KAON:** http://kaon.semanticweb.org/
- **DOGMA:** M Jarrar, J Demey, R Meersman *"On Using Conceptual Data Modeling for Ontology Engineering",* Journal on Data Semantics, 2003 – Springer Verlag
- **MADS:** Christine Parent , Stefano Spaccapietra ,Esteban Zimányi, "*Spatio-temporal conceptual models: data structures + space + time*", Proc. 7th ACM international Symp. on Advances in Geographic Information Systems, Kansas City, USA,1999

Reasoning services

Services for the Tbox

- Subsumption: verifies if a concept C is subsumed by (is a subconcept of) another concept D
- Consistency: verifies that there exists at least one interpretation I which satisfies the given Tbox
- Local Satisfiability: verifies, for a given concept C, that there exists at least one interpretation in which C is true.

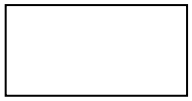
Services for the Abox

- Consistency: verifies that an Abox is consistent with respect to a given Tbox
- Instance Checking: verifies if a given individual x belongs to a particular concept C
- Instance Retrieval: returns the extension of a given concept C, that is, the set of individuals belonging to C.

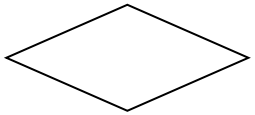
Comparison

- analysis of the features of a descriptive ontology (data structures, instance management, constraint definition, queries)
- compare these features with the functionality provided by current representation approaches from the database world

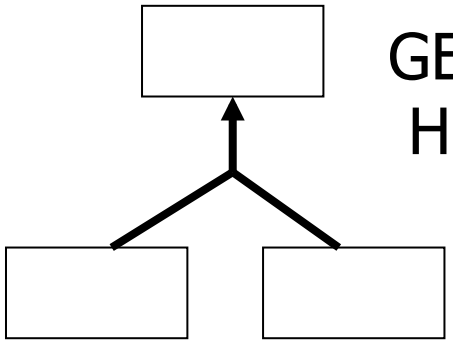
e.g. ER vs.ontology



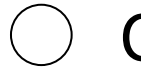
ENTITY



RELATIONSHIP

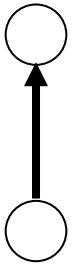


GENERALIZATION HIERARCHY



CONCEPT

RELATION



ISA

ATTRIBUTE

DATA TYPE PROPERTY

Comparison

Descriptive ontologies require rich models to enable representations close to human perception

	DL	DB
Complex data structures	**No**	**yes**
Generalization/ specialization hierarchies	**yes**	**yes**
Defined concepts	**yes**	**no**

DB versus ontologies

How should we improve database conceptual models to fulfill ontology requirements ?

- Supporting defined concepts and adding the necessary reasoning mechanisms
- Managing missing and incomplete information: semantic differences between the two assumptions made w.r.t. missing information (*Closed World Assumption* vs. *Open World Assumption*)

How can ontologies support integration?

- An ontology instead of a global schema
- An ontology as a schema integration support tool
  - An ontology as a support tool for content interpretation and wrapping (e.g. HTML pages)
  - An ontology as a support tool for content inconsistency detection and resolution

Ontologies and integration problems

- Discovery of "equivalent" concepts (mapping)
  - What does equivalent mean?
- Formal representation of these mappings
  - How are these mappings represented?
- Reasoning on these mappings
  - How do we use the mappings within our reasoning and query-answering process?

Ontology *matching*

- The process of finding pairs of resources coming from different ontologies which can be considered equal in meaning – *matching operators*
- The similarity value is usually a number in the interval [0,1]
- It is an input to the different approaches to integration, described below
- Mediation may be done without integrating the ontologies, but using the matchings in different ways

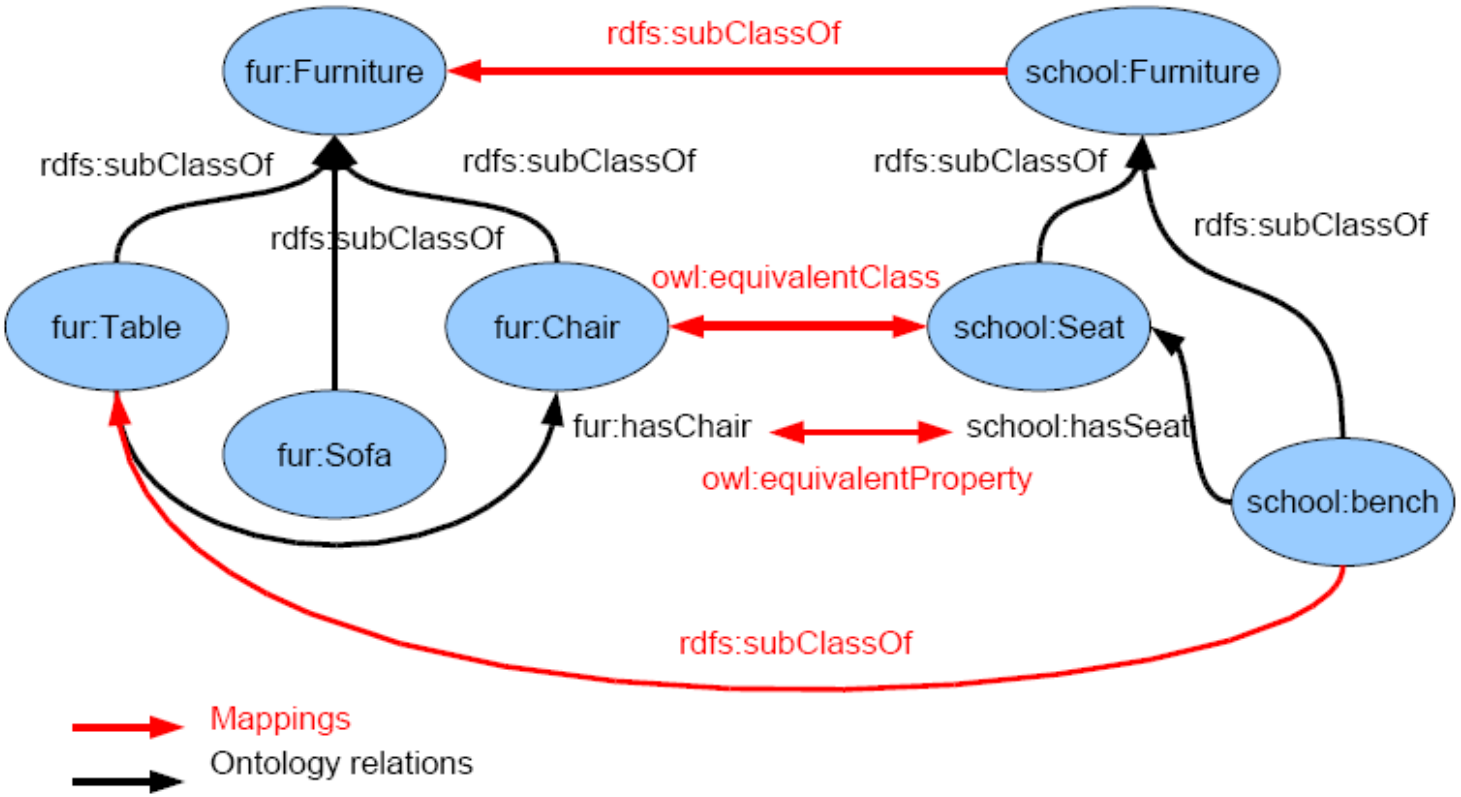
Similarity operator properties

- $sim(x,y) \in [0..1]$
- $sim(x,y) = 1 \leftrightarrow x = y$
- $sim(x,y) = 0 \leftrightarrow x \neq y$
- $sim(x,x) = 1$ (sim is reflexive)
- $sim(x,y) = sim(y,x)$ (sim is symmetric)
- $sim(x,z) \leq sim(x,y) + sim(y,z)$ (The triangular inequation holds)

Ontology mapping

- The process of relating similar concepts or relations of two or more information sources using equivalence relations or order relations.
- These relations are commonly implemented in inference and reasoning softwares, so we can use the output ontology to perform complex tasks on them without extra effort.

Ontology mapping



Reasons for ontology mismatches

At the definition language level:

- Syntax
- Availability of different constructs (e.g. part-of, synonym, etc.)
- Linguistic primitives' semantics (e.g. union or intersection of multiple intervals)

→ Normalize by translating to the same language/ paradigm

Reasons for ontology mismatches

At the ontology level:

- Scope: Two classes seem to represent the same concept, but do not have exactly the same instances
- Model coverage and granularity: a mismatch in the part of the domain that is covered by the ontology, or the level of detail to which that domain is modelled.
- Paradigm: Different paradigms can be used to represent concepts such as time. For example, one model might use temporal representations based on continuous intervals while another might use a representation based on discrete sets of time points.
- Encoding

Reasons for ontology mismatches

At the ontology level:

- **Concept description: e.g. a distinctions between two classes can be modeled using a qualifying attribute or by introducing a separate class, or the way in which is-a hierarchy is built**
- **Homonymies**
- **Synonymies**

How can ontologies support integration?

An ontology as a schema integration support tool

- Ontologies used to represent the semantics of schema elements (if the schema exists)
- Similarities between the source ontologies guide conflict resolution
  - At the schema level (if the schemata exist)
  - At the instance level

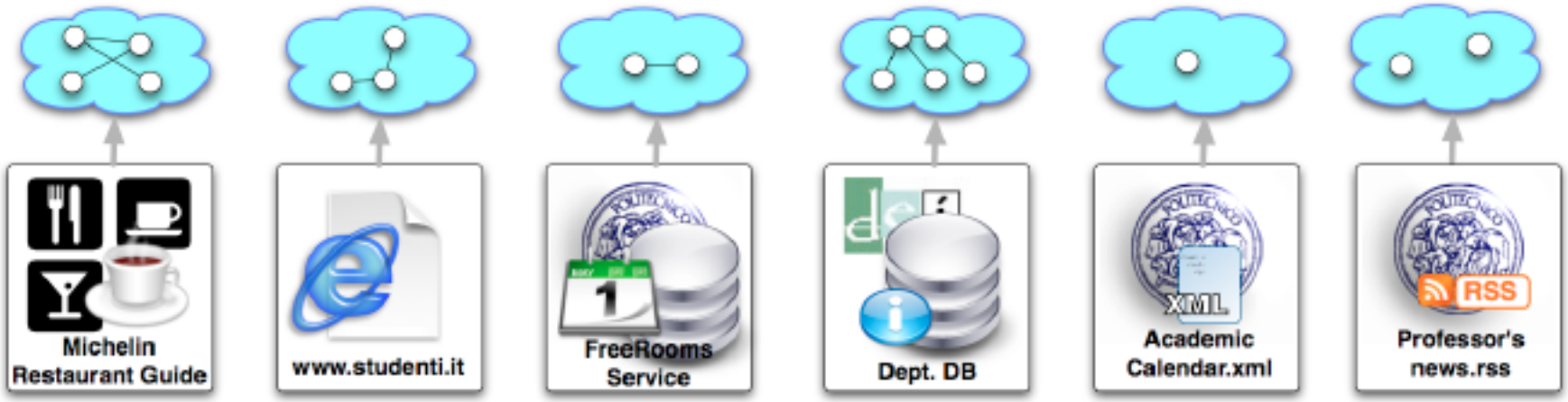
How can ontologies support integration?

An ontology instead of a global schema:

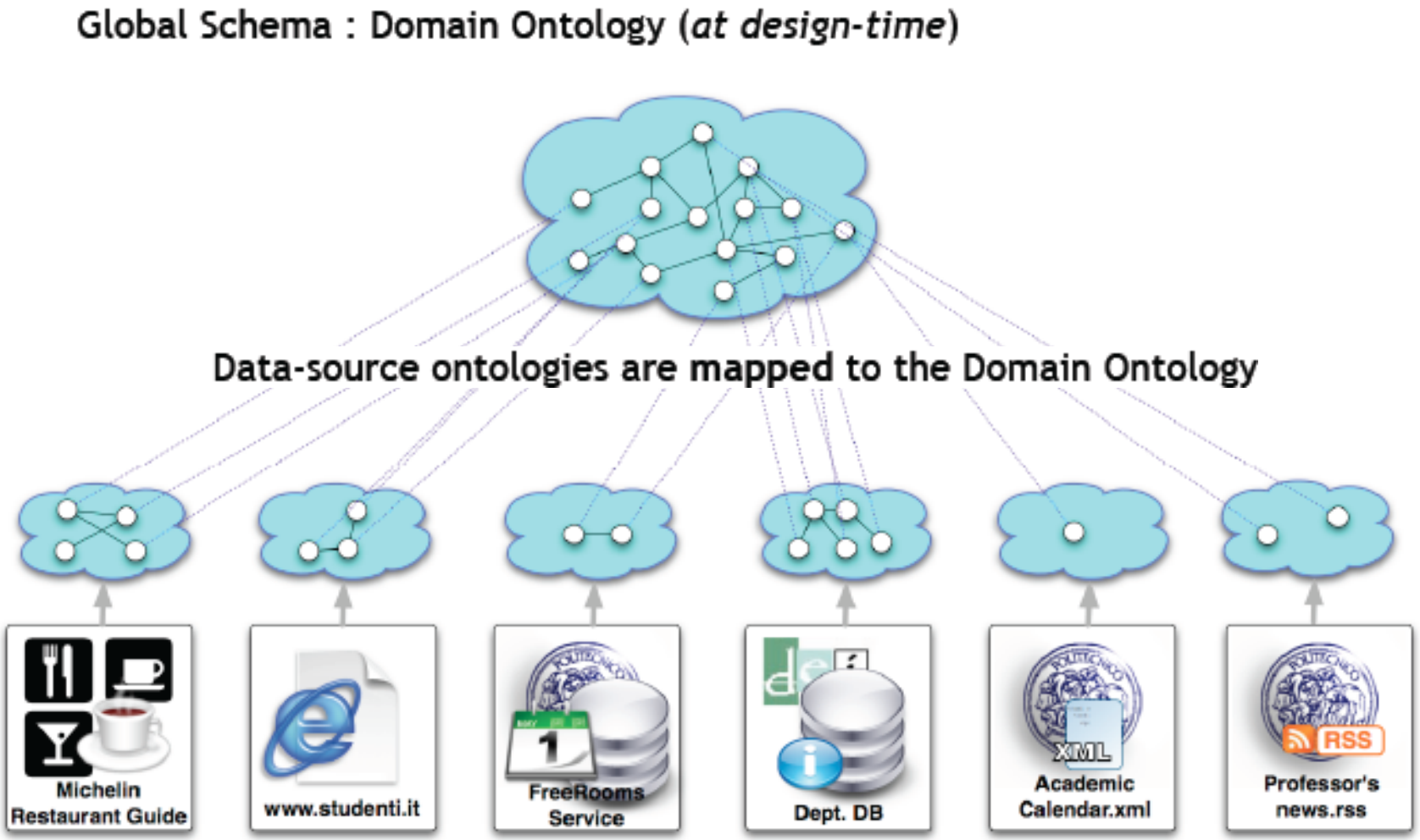
- Intensional-level representation only in terms of ontologies
- Ontology mapping, merging, etc. instead of schema integration
- Integrated ontology used as a schema for querying

An ontology instead of a global schema

- Data-source heterogeneity is solved by extracting the semantics in an ontological format (potentially *at run-time*)
- Automatic Wrapper generation + Query translation will bridge among two models.
- Not an easy task:
  - several issues, e.g., impedance mismatch
  - unstructured data sources



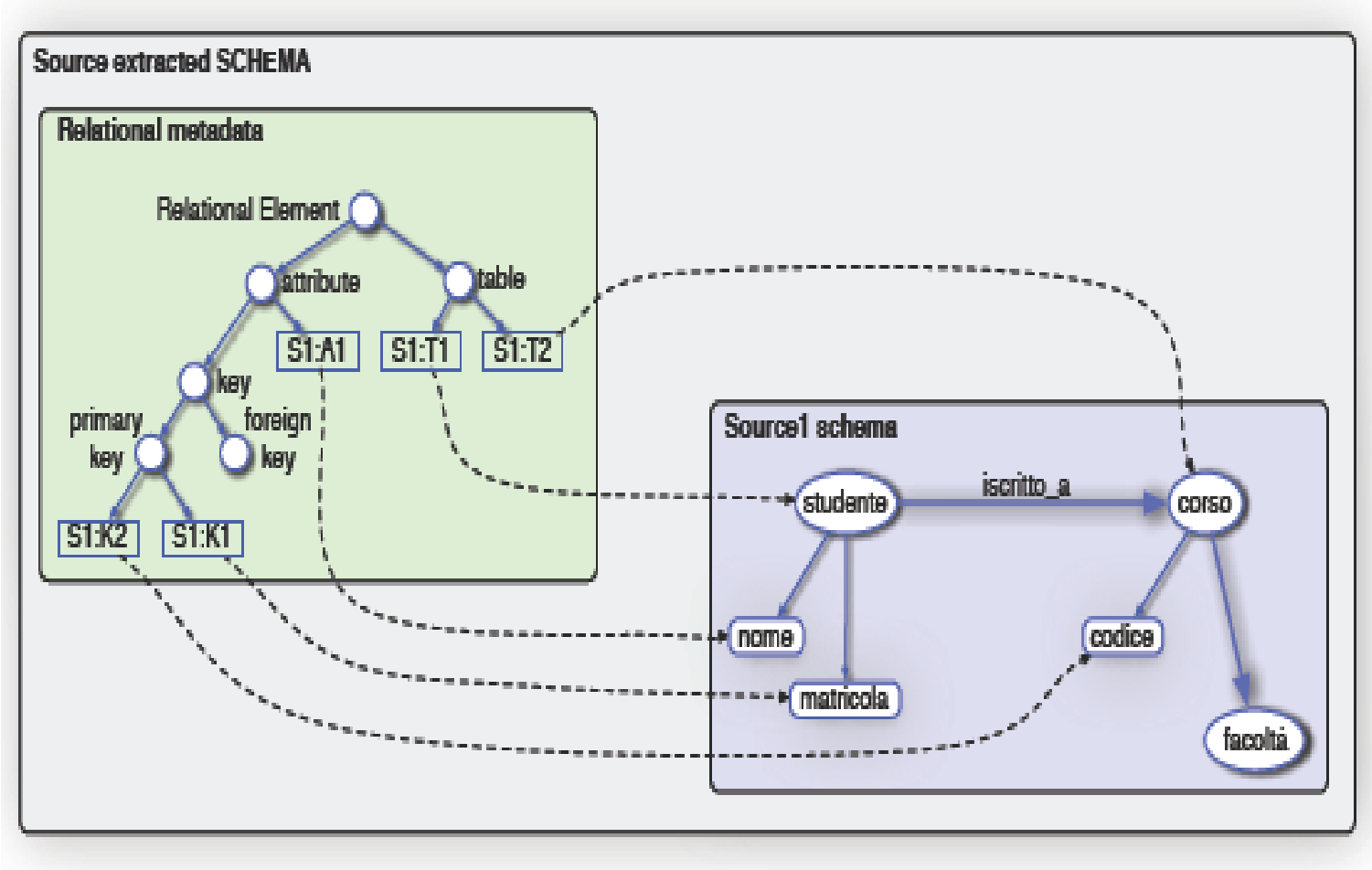
An ontology instead of a global schema



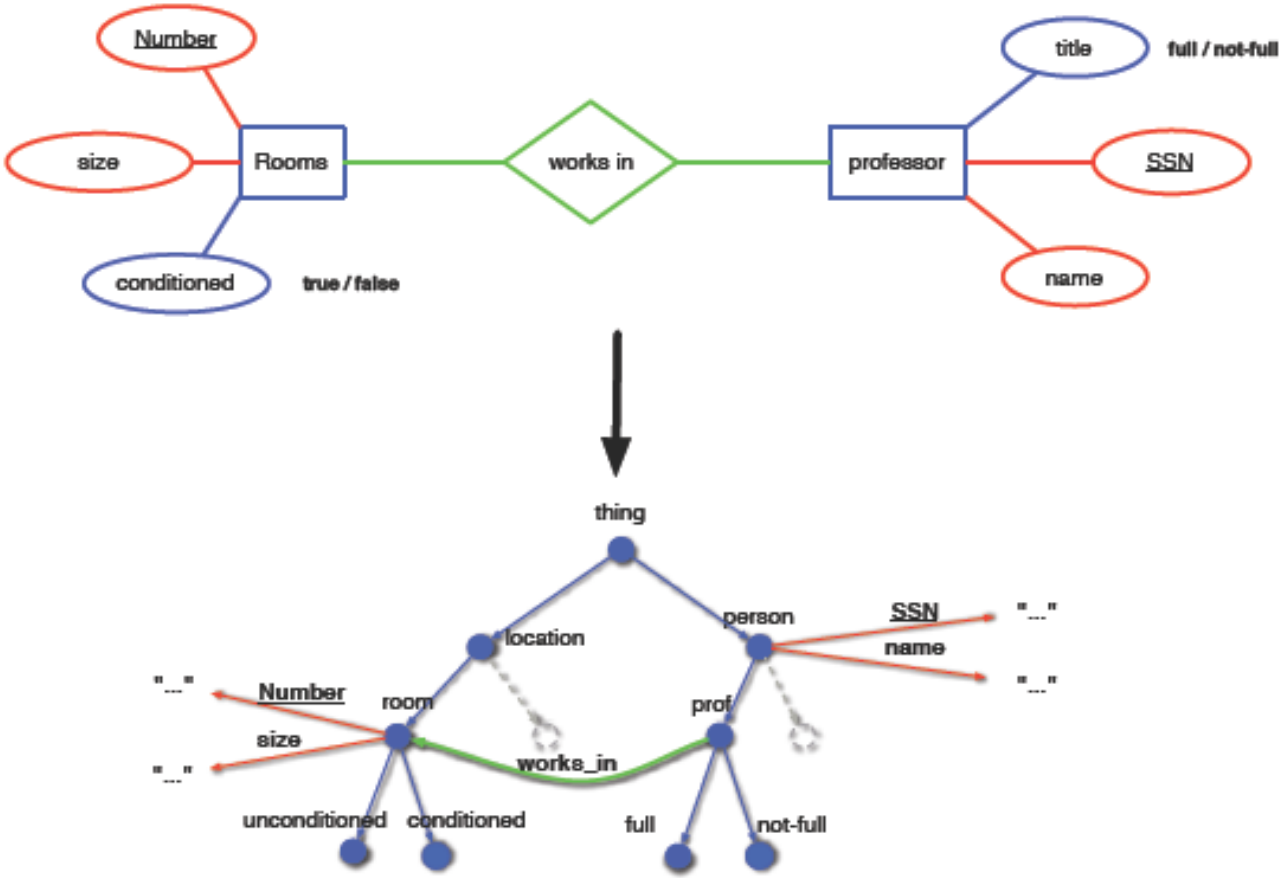
How can ontologies support integration?

- An ontology as a support tool for content interpretation and wrapping (e.g. HTML pages)
- An ontology as a support tool for content inconsistency detection and resolution

Ontology extraction from a relational schema



Ontology extraction from a ER schema



Query processing

Ontologies require **query languages** allowing

- Schema exploration
- Reasoning on the schema
- Instance querying (where does the instance sit?)
- E.g. SPARQL (W3C)

Query processing when instances are kept in a database

- Transformation of ontological query into the language of the datasource, and the other way round
- Different semantics (CWA versus OWA)
- What has to be processed where (e.g. push of the relational operators to the relational engine)