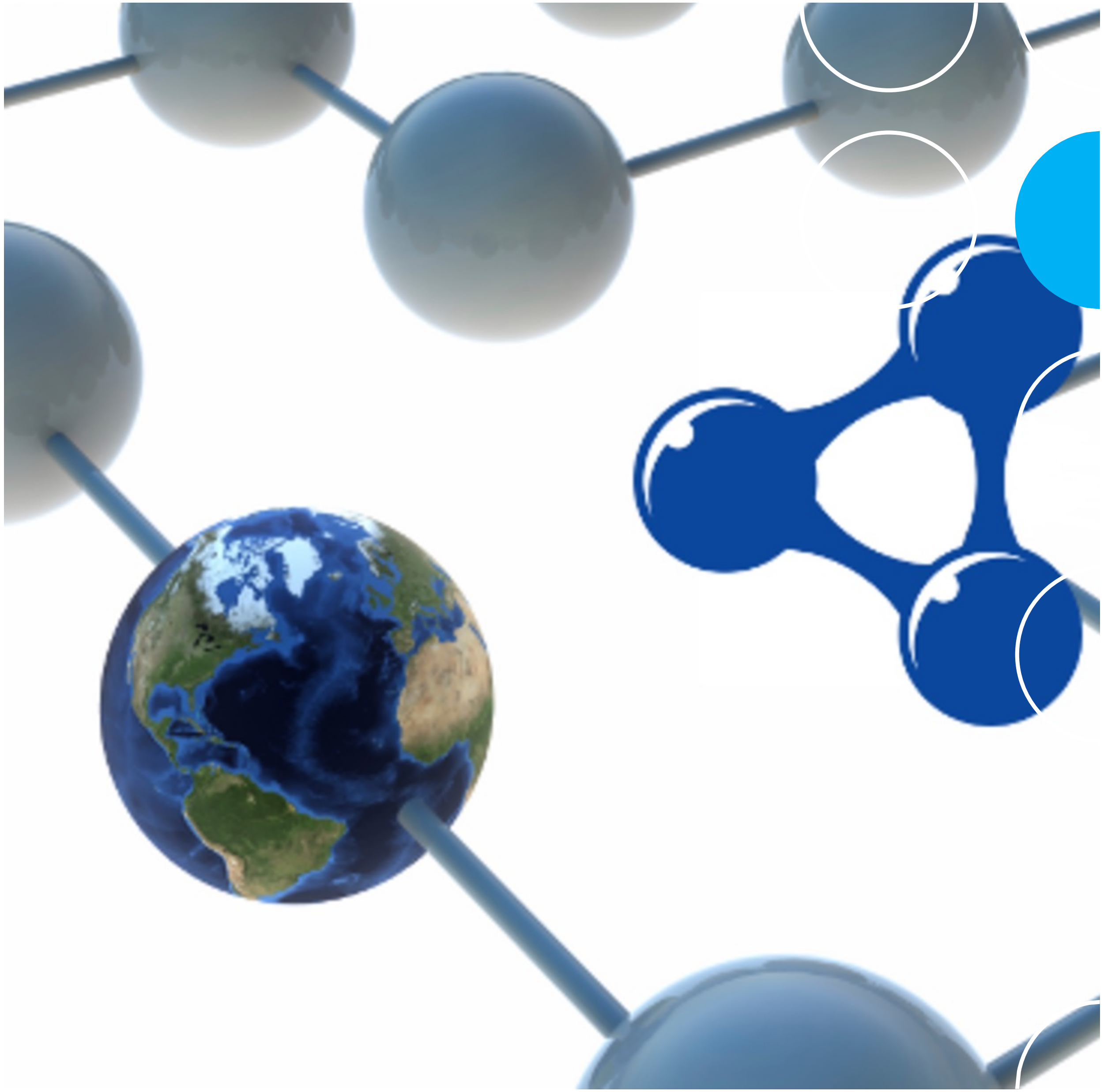
Semantic Web and Linked Data



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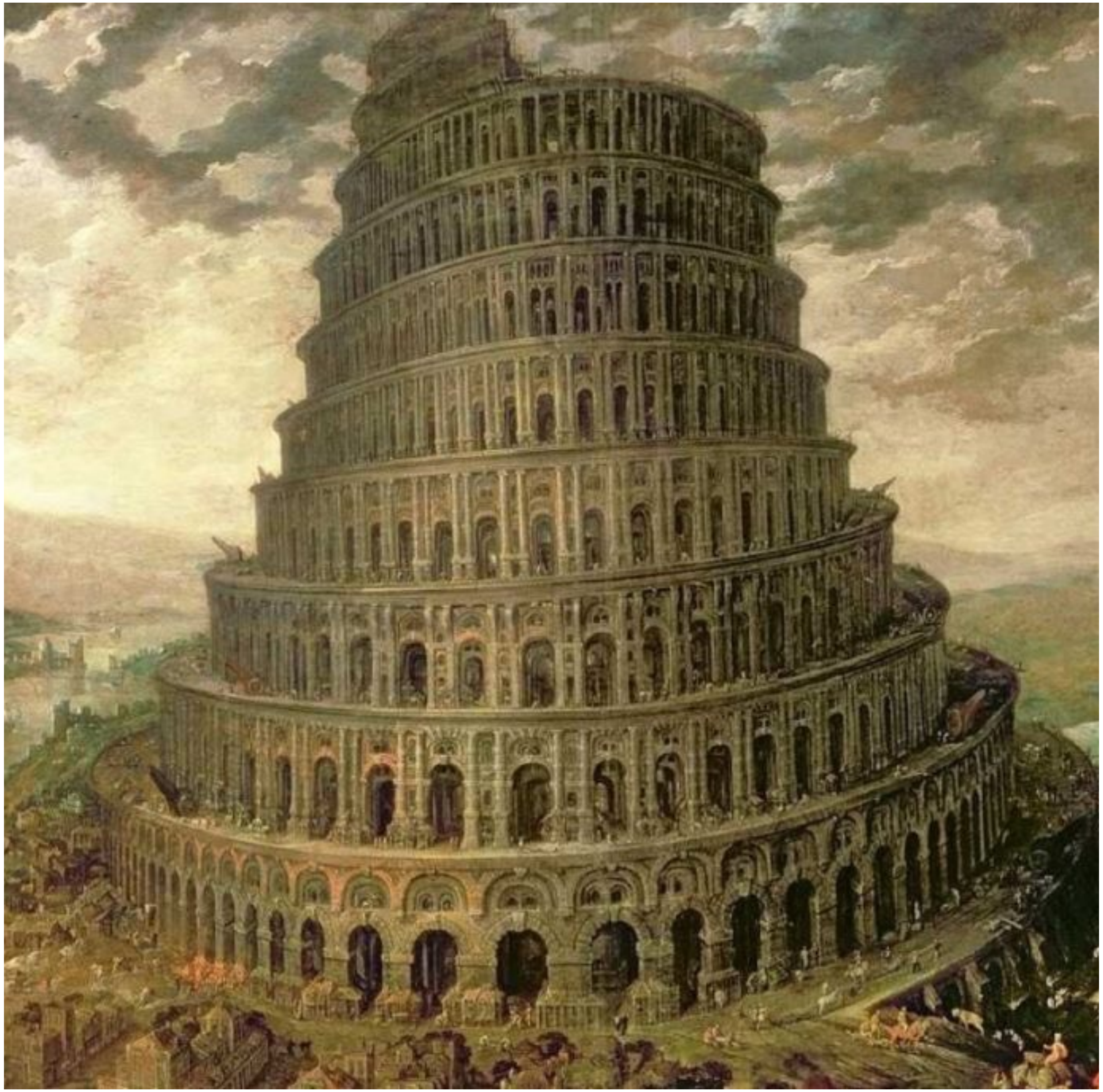
Class 7: Learning Objectives

- Ontologies.
- Types of ontologies.

- The OWL ontology language
  - Logic and Inference.
  - The Protégé open-source tool.



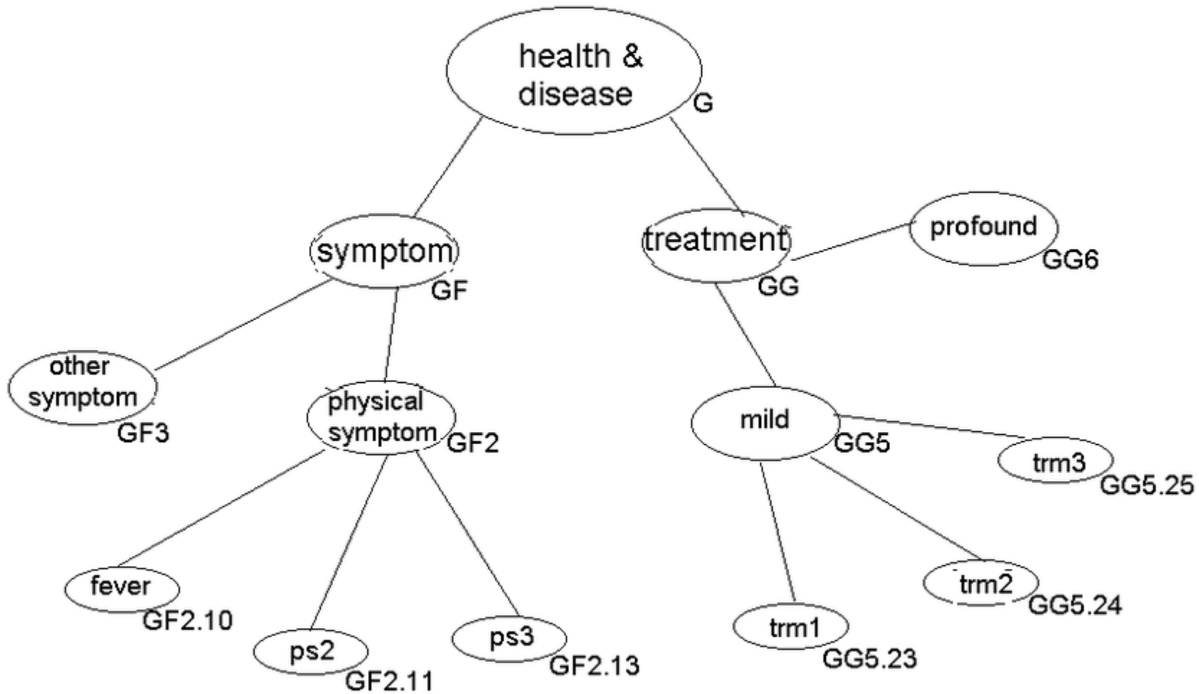
People can’t share knowledge if they don’t speak a common language.

Steps to knowledge sharing

- Common symbols and concepts (**Syntax**)
- Agreement about their meaning (**Semantics**)
- Classification of concepts (**Taxonomy**)
- Associations and Relations of concepts (**Thesauri**)
- Rules and knowledge about which relations are allowed and make sense (**Ontologies**)

Ontology

An ontology provides a specification of what exists in some domain of interest.



An ontology is...

- Something in your head
- A data structure in a computer
- A set of terms and relationships that we share to ensure we are communicating consistently

Ontologies

Ontologies are a popular research topic in Artificial Intelligence (AI), e.g.:

- Knowledge Engineering, Natural Language Processing, Intelligent Information Integration and Multi-agent systems.

By attaching information to data that describe its contents and meaning, web resources can be used by machines.

The data can be used not just for display purposes, but also for automation, integration and reuse of data across various applications.

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What is an ontology?

Studer(98): Formal, explicit specification of a shared conceptualization

Machine readable

Consensual knowledge

Concepts, properties, functions, axioms are explicitly defined

Abstract model of some domain

Ontology

What exists in a domain and how they relate with each other.

- In general, an ontology formally describes a domain of discourse.
- An ontology consists of a finite list of terms (i.e. concepts) and the relationships between the terms (i.e. properties).
- The terms denote important concepts (classes of objects) of the domain.
- For example, in a university setting: staff members, students, courses, modules, lecture theatres, and schools are some important concepts.

For what is an ontology good for?

Enable knowledge sharing and knowledge reuse.

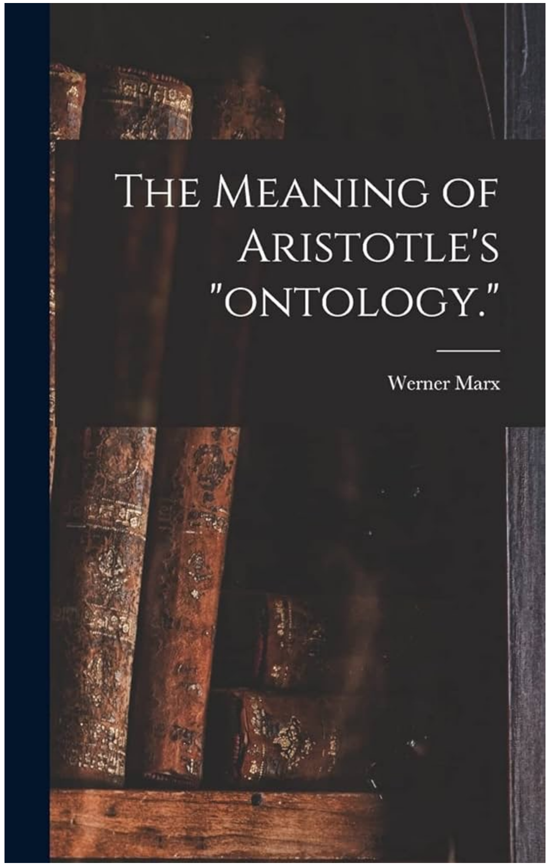
- Ontologies capture general knowledge about a domain that is changing rarely and specify concepts and relations about which knowledge is to be accumulated and processed.

- For information systems or for the Internet, ontologies can be used to organize keywords and database concepts by capturing the semantic relationships among the keywords or among the tables and fields in a database.

What is an Ontology?

A data structure that specifies, for a given application area:

- Entities
- Properties of entities
- Relationships among entities



Why develop an ontology?

1. To share a **common understanding** of the entities in a given domain
    - among people
    - among software agents
    - between people and software
2. To enable **reuse** of data and information
    - to avoid re-inventing the wheel
    - to introduce standards to allow interoperability and automatic reasoning
3. To create **communities of researchers**

Criteria for Introducing Ontologies

- Large amounts of data
  - Data available on the Web
  - Data acquired or generated by new techniques
- Complex data structures
  - Inheritance, containment and other hierarchies
  - Many relationships
- Diverse sources
  - Many legacy systems
  - Sources on the Web using different formats
- Requirement for formal proofs
  - Contracts and policy enforcement

Terminological Systems

Terminological systems can be seen as basic examples of ontologies; for example:

Terminologies	list of terms referring to concepts in a particular domain;
Thesaurus	terms are ordered alphabetically and concepts maybe described by synonymous terms;
Vocabulary	concepts are defined in formal or free text form;
Classification	concepts are organized using generic (i.e. is_a) relationships;
Coding systems	codes designate concepts.

Ontology Elements

- Concepts(classes) + their hierarchy
- Concept properties (slots/attributes) + their hierarchy
- Property restrictions (type, cardinality, domain ...)
- Relations between concepts (disjoint, equality ...)
- Instances

Ontology Languages

- Ontologies are formal theories about a certain domain of discourse and therefore require a formal logical language to express them.
- Languages for defining ontologies are syntactically and semantically rich languages, e.g. richer than common approaches for databases.

The OWL Language

- Web Ontology Language (OWL) is the W3C recommendation for representing ontologies on the Web;
- OWL is a semantic markup language for defining, publishing and sharing ontologies in the World Wide Web;
- OWL contains specific constructs to represent the domain and range of properties, subclass and other axioms and constraints on the values that can be assigned to the property of an object;
- OWL is based on Description Logics knowledge representation formalism.

The OWL Language

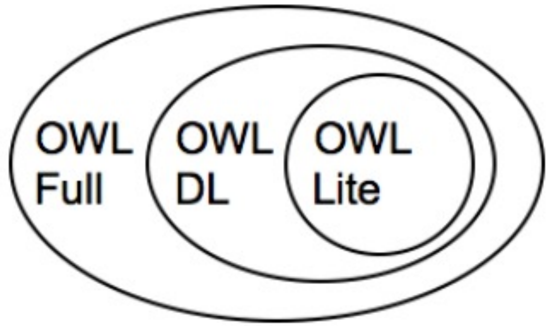
- OWL is a W3C Recommendation
  - OWL was published in 2004
  - OWL 2 was published in 2012
- Motivations:
  - A well-defined syntax
  - A formal semantics
  - Efficient reasoning support

OWL and Description Logic

- OWL (DL) benefits from extensive work on DL research:
  - Well defined semantics
  - Formal properties (describing complexity, and providing decidability)
  - Known reasoning algorithms
  - Implemented systems

OWL “flavors”

- W3C’s Web Ontology Working Group defined OWL as three different sublanguages:
  - OWL Full
  - OWL DL
  - OWL Lite



- Each sublanguage geared toward fulfilling different aspects of requirements

OWL DL

- OWL DL (Description Logics)
  - Based on FOL semantics

- OWL DL permits efficient reasoning support
  - The most expressive decidable OWL sub-language

- But we lose full compatibility with RDF:
  - Every legal OWL DL document is a legal RDF document.
  - Not every RDF document is a legal OWL DL document.

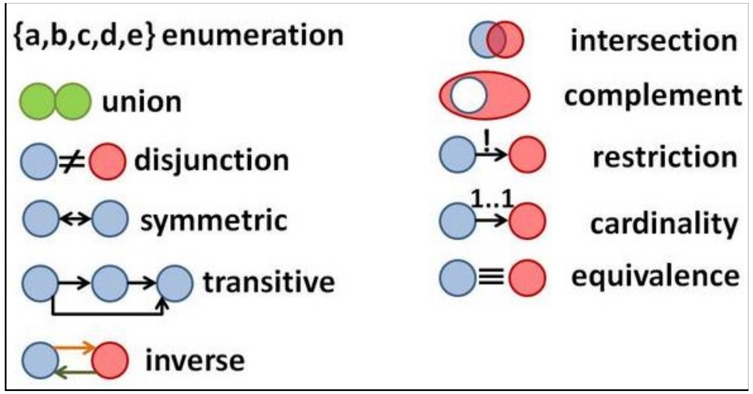
OWL constructs for classes vs DL concepts

OWL construct	DL	Example
owl:Thing	$\top$	
owl:Nothing	$\bot$	
intersectionOf($C_1 \ldots C_n$)	$C_1 \sqcap \cdots \sqcap C_n$	**Human** $\sqcap$ **Male**
unionOf($C_1 \ldots C_n$)	$C_1 \sqcup \cdots \sqcup C_n$	**Doctor** $\sqcup$ **Lawyer**
complementOf(C)	$\neg C$	$\neg$**Male**
oneOf($a_1 \ldots a_n$)	$\{a_1, \ldots, a_n\}$	**{john, mary}**
restriction(r allValuesFrom(C))	$\forall r.C$	$\forall$**hasChild.Doctor**
restriction(r someValuesFrom(C))	$\exists r.C$	$\exists$**hasChild.Doctor**
restriction(r minCardinality(C))	$\geq n\ r.C$	≥ 2 **hasChild.Lawyer**
restriction(r maxCardinality(C))	$\leq n\ r.C$	≤ 2 **hasChild.Lawyer**
restriction(r value(a))	$\exists r.\{a\}$	$\exists$**citizen_of.{France}**

OWL class relationships vs DL inclusions

OWL axiom	DL	Example
Class(A partial $C_1 \ldots C_n$))	$A \sqsubseteq C_1 \sqcap \ldots C_n$	**Human** $\sqsubseteq$ **Physical_Object**
Class(A complete $C_1 \ldots C_n$))	$A \equiv C_1 \sqcap \ldots C_n$	**Man** $\equiv$ **Human** $\sqcap$ **Male**
SubClassOf(C_1 C_2)	$C_1 \sqsubseteq C_2$	**Human** $\sqsubseteq$ **Animal** $\sqcap$ **Biped**
EquivalentClasses(C_1 C_2)	$C_1 \equiv C_2$	**Man** $\equiv$ **Human** $\sqcap$ **Male**
DisjointClasses(C_1 C_2)	$C_1 \sqsubseteq \neg C_2$	**Male** $\sqsubseteq$ $\neg$**Female**
SameIndividual(a_1 a_2)	$\{a_1\} \equiv \{a_2\}$	PresidentBush=G.W.Bush
DifferentIndividual(a_1 a_2)	$\{a_1\} \sqsubseteq \neg\{a_2\}$	Bush$\neq$Obama

OWL on one Slide



- **Symmetric**: if P(x, y) then P(y, x)
- **Transitive**: if P(x,y) and P(y,z) then P(x, z)
- **Functional**: if P(x,y) and P(x,z) then y=z
- **InverseOf**: if P1(x,y) then P2(y,x)
- **InverseFunctional**: if P(y,x) and P(z,x) then y=z
- **allValuesFrom**: P(x,y) and y=allValuesFrom(C)
- **someValuesFrom**: P(x,y) and y=someValuesFrom(C)
- **hasValue**: P(x,y) and y=hasValue(v)
- **cardinality**: cardinality(P) = N
- **minCardinality**: minCardinality(P) = N
- **maxCardinality**: maxCardinality(P) = N

- **equivalentProperty**: P1 = P2
- **intersectionOf**: C = intersectionOf(C1, C2, …)
- **unionOf**: C = unionOf(C1, C2, …)
- **complementOf**: C = complementOf(C1)
- **oneOf**: C = one of(v1, v2, …)
- **equivalentClass**: C1 = C2
- **disjointWith**: C1 != C2
- **sameIndividualAs**: I1 = I2
- **differentFrom**: I1 != I2
- **AllDifferent**: I1 != I2, I1 != I3, I2 != I3, …
- **Thing**: I1, I2, …

Caption:

- Properties are indicated by: P, P1, P2, etc
- Specific classes are indicated by: x, y, z
- Generic classes are indicated by: C, C1, C2
- Values are indicated by: v, v1, v2
- Instance documents are indicated by: I1, I2, I3, etc.
- A number is indicated by: N
- P(x,y) is read as: “property P relates x to y”

An example

- Woman $\equiv$ Person $\sqcap$ Female
- Man $\equiv$ Person $\sqcap$ $\neg$Woman
- Mother $\equiv$ Woman $\sqcap$ $\exists$hasChild.Person
- Father $\equiv$ Man $\sqcap$ $\exists$hasChild.Person
- Parent $\equiv$ Father $\sqcup$ Mother
- Grandmother $\equiv$ Mother $\sqcap$ $\exists$hasChild.Parent

We can further infer (though not explicitly stated):

→ Grandmother $\sqsubseteq$ Person

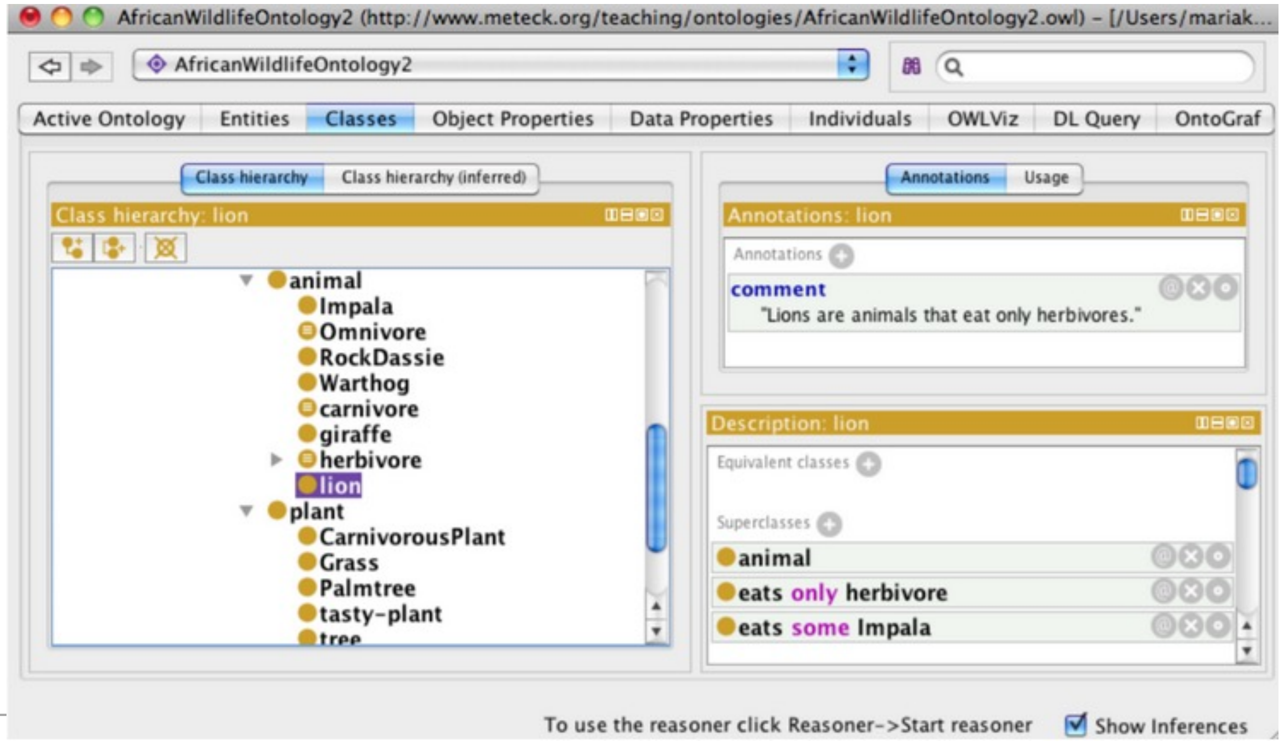
Grandmother $\sqsubseteq$ Man $\sqcup$ Woman

etc.

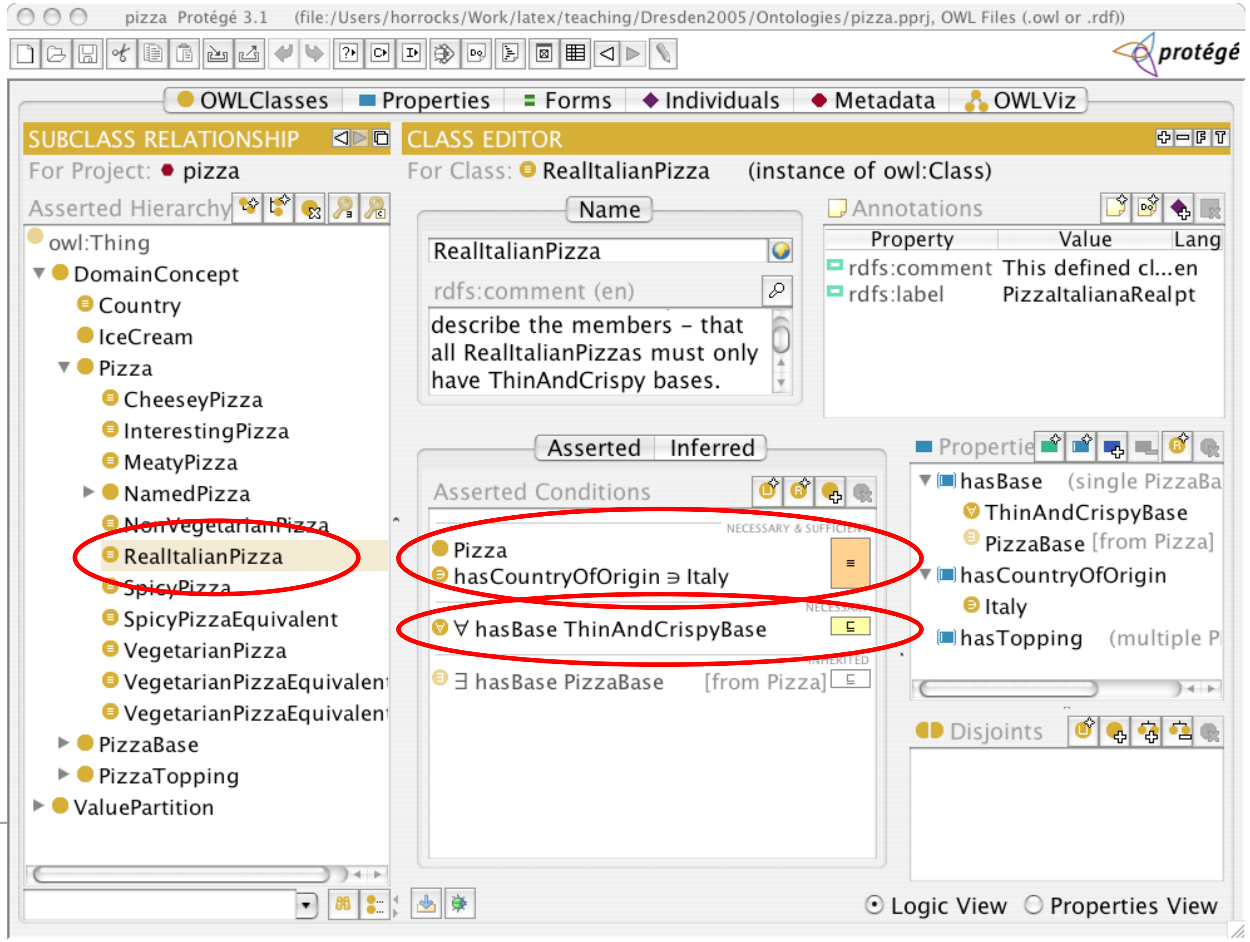
A Sample Ontology

African Wildlife Ontology (AWO)

In Protégé tool:



Example Ontology (Protégé)



The Web Ontology Language (OWL) provides concepts for detailed ontologies.

- RDFS captures basic ontological relations but lacks several common and important concepts.
  - cardinality restrictions on properties
  - inverse, symmetric, and transitive properties
  - equality and disjointness
  - …
- OWL extends RDFS with advanced concepts.
  - RDFS and OWL are used side by side.

OWL defines additional constraints for individuals, properties, and classes.

restrictions on individuals

`owl:sameAs`, `owl:differentFrom`, …

restrictions on properties

`owl:ObjectProperty`, `owl:inverseOf`, `owl:FunctionalProperty`, …

restrictions on classes

`owl:intersectionOf`, `owl:Restriction`, …

OWL defines its own version of resources and classes.

The class of everything is `owl:Thing`.

similar to `rdfs:Resource`

The class of classes is `owl:Class`.

subclass of `rdfs:Class`

An IRI uniquely identifies a resource, but one resource can have many IRIs.

- You cannot assume just because 2 IRIs are different they necessarily point to different resources.
  - `ex:Tom a ex:Cat.`
  - `ex:Jerry a ex:Mouse.`

- You cannot conclude ex:Tom and ex:Jerry are different.

An IRI uniquely identifies a resource, but one resource can have many IRIs.

owl:sameAs indicates two resources are the same.

owl:differentFrom indicates two resources differ.

```
ex:Tom owl:differentFrom ex:Jerry.
```

Typical properties can either take a literal or a named node as object.

Properties taking only literal values as object are instances of owl:DataTypeProperty.

```
foaf:givenName a owl:DataTypeProperty.
foaf:givenName rdfs:range rdfs:Literal.
```

Typical properties can either take a literal or a named node as object.

Properties taking only non-literal values as object are instances of `owl:ObjectProperty`.

```
foaf:knows a owl:ObjectProperty.
foaf:knows rdfs:range _:NonLiterals.
_:NonLiterals owl:complementOf rdfs:Literal.
```

Inverse properties express a triple in the opposite direction.

One property is the `owl:inverseOf` another if it asserts the same relation from object to subject.

```
ex:TimBL foaf:made dbr:World_Wide_Web.
dbr:World_Wide_Web foaf:maker ex:TimBL.
foaf:made owl:inverseOf foaf:maker
```

Inverse properties express a triple in the opposite direction.

Ontologists typically pick *one* property direction.

Different ontologies might choose different directions.

`owl:inverseOf` allows to connect such properties.

A functional property restricts the objects for a given subject to be identical.

If any subject can at most have one unique value for some property, it's an `owl:FunctionalProperty`.

```
ex:Delphine ex:hasBiologicalFather ex:Albert.
ex:hasBiologicalFather a
owl:FunctionalProperty.
```

A functional property restricts the objects for a given subject to be identical.

The inverse is `owl:InverseFunctionalProperty`.

```
ex:Albert ex:isBiologicalFatherOf ex:Delphine.
ex:isBiologicalFatherOf a
owl:InverseFunctionalProperty.
```

Functional properties have strong effects, so you must understand them well.

What is the logical consequence of the following?

```
ex:Delphine ex:hasBiologicalFather ex:Albert.
ex:Delphine ex:hasBiologicalFather ex:Jacques.
ex:hasBiologicalFather a owl:FunctionalProperty.
```

Functional properties have strong effects, so you must understand them well.

It might be counterintuitive, but the conclusion is:

```
ex:Albert owl:sameAs ex:Jacques.
```

To arrive at a contradiction, explicitly define inequality:

```
ex:Albert owl:differentFrom ex:Jacques.
```

OWL contains similar properties for symmetry, reflexivity, and transitivity.

Exercise:

Consulting W3C OWL Specifications, define these properties and identify some examples of each.

OWL

Simple Classes and Individuals

- An important use of an ontology will depend on the ability to reason about individuals.
  - This requires a mechanism to describe the classes that individuals belong to and the properties that they inherit by virtue of class membership.
  - We can always assert specific properties about individuals, but much of the power of ontologies comes from class-based reasoning.
- Sometimes we want to emphasize the distinction between a class as an object and a class as a set containing elements.
  - The set of individuals that are members of a class are called the extension of the class.

Simple Named Classes

- Every individual in the OWL world is a member of the class owl:Thing.
- Named classes
  - Example:

```
<owl:Class rdf:ID="Staff"/>
<owl:Class rdf:ID="Researcher"/>
<owl:Class rdf:ID="Academic"/>
```

- The fundamental taxonomic constructor for classes is rdfs:subClassOf.
  - Example:

```
<owl:Class rdf:ID="Researcher">
<rdfs:subClassOf rdf:resource="#Staff" />
...
</owl:Class>
```

Individuals

- Individuals enable us to describe members of a class.
- An individual is minimally introduced by declaring it to be a member of a class.

```
<owl:Thing rdf:ID="Postdoc" />
  <owl:Thing rdf:about="#Postdoc">
        <rdf:type rdf:resource="#Researcher"/>
  …
 </owl:Thing>
```

- rdf:type is an RDF property that ties an individual to a class of which it is a member.

Simple Properties

- *Properties* allow asserting general facts about the members of classes and defining specific facts about individuals.
- A property is a binary relation.
- Two types of properties are distinguished:
  - *datatype properties*, relations between instances of classes and RDF literals and XML Schema datatypes
  - *object properties*, relations between instances of two classes.

Simple Properties- Example

```
<owl:ObjectProperty rdf:ID="hasSupervisor">
  <rdfs:domain rdf:resource="# PhDStudent "/>
  <rdfs:range rdf:resource="#Academic"/>
</owl:ObjectProperty>

<owl:ObjectProperty rdf:ID="demonstratedBy">
  <rdfs:domain rdf:resource="#Lab" />
  <rdfs:range rdf:resource="#PhDStudent" />
</owl:ObjectProperty>
```

Simple Properties- Example

Using DatatypeProperty

```
<owl:Class rdf:ID="hasName" />
<owl:DatatypeProperty rdf:ID="nameValue">
  <rdfs:domain rdf:resource="#PhDStudent" />
  <rdfs:range rdf:resource="&xsd; string"/>
</owl:DatatypeProperty>
```

Simple Properties- Constraints

```
<owl:Class rdf:ID="PhDStudent">
  <rdfs:subClassOf rdf:resource="#DeptMembers"/> <rdfs:subClassOf>
      <owl:Restriction>
        <owl:onProperty rdf:resource="#hasSupervisor"/>
        <owl:minCardinality
      rdf:datatype="&xsd;nonNegativeInteger">1</owl:minCardinality>
      </owl:Restriction>
  </rdfs:subClassOf>
...
</owl:Class>
```

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Ontology design
Philosophical principles

1. Clarity: understandable not only for machines but also for humans.
2. Coherence: consistency of formal and informal layers of ontology (axioms vs. natural language documentation and labels).
3. Extendibility
4. Minimal coding bias: specification of ontologies should remain at the knowledge level (if it is possible) without depending on a particular symbol-level encoding.
5. Minimal ontological commitment: defining only those terms that are essential to the communication of knowledge consistent theory.
6. Proper sub-concept taxonomies

Ontology design
Technical principles

1. Define and use of naming conventions
   - Capitalisation: it is a common convention to begin concept names with capital, instance and property names with non-capital letters.
   1. Delimiters: common conventions are using space or “-” or writing names in CamelCase which eliminates the need for delimiters.
   2. Singular or plural: it is common to use the singular form in the concept names.
2. Scoping the ontology
   1. Introducing new entities: introduce a new concept only if it is significant for the problem domain.

Ontology design principles
Technical principles (cont.)

3. Optimal number of sub-concepts;
    - New concept or property value - concept or instance?
        - If it is meaningful to speak of a “kind of X” in the target domain i.e. the entity represents a set of something, make X a concept. Otherwise X should be an instant.
4. Document your ontologies;
5. Represent disjoint and exhaustive knowledge explicitly.

Further Reading OWL

- Industry-scale Knowledge Graphs: Lessons and Challenges

https://queue.acm.org/detail.cfm?ref=rss&id=3332266

- Protégé Tutorials:

1. https://www.emse.fr/~zimmermann/Teaching/SemWeb/Practice/ProtegeTutorial.pdf
2. https://protege.stanford.edu/publications/ontology_development/ontology101.pdf

Sources

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