Chapter 4

OWL

Based on slides from Grigoris Antoniou and Frank van Harmelen
TL;DR: What is OWL

OWL defines new RDF predicates to RDF making it more expressive A knowledge representation language
Outline

1. A bit of history
2. Basic Ideas of OWL
3. The OWL Language
4. Examples
5. The OWL Namespace
6. OWL 2
The OWL Family Tree

- **Logic Programming (1970s)**
- **Frames (1974)**
- **Description Logic (1980s)**
- **SHOE (1996)**
- **RDF/RDF(S)**
- **DAML+OIL (~2002)**
- **OntoKnowledge+Others (~2002)**
- **Joint EU/US Committee (~2002)**
- **W3C (2004)**
- **OWL**
A Brief History of OWL: SHOE

- Simple HTML Ontology Extensions

SHOE allows World-Wide Web authors to annotate their pages with ontology-based knowledge about page contents. We present examples showing how the use of SHOE can support a new generation of knowledge-based search and knowledge discovery tools that operate on the World-Wide Web.

- Add “semantic” tags defined in an ontology plus prolog-like rules to Web pages
A Brief History of OWL: SHOE

<META HTTP-EQUIV="Instance-Key"
CONTENT="http://www.cs.umd.edu/~george">

<USE-ONTOLOGY
"our-ontology" VERSION="1.0" PREFIX="our"
URL="http://ont.org/our-ont.html">

...

<CATEGORY "our.Person">
<RELATION "our.firstName" TO="George">
<RELATION "our.lastName" TO="Cook">
<RELATION "our.marriedTo" TO="http://cs.umd.edu/~helena">
<RELATION "our.employee" FROM="http://cs.umd.edu">
A Brief History of OWL: OIL

- Developed by group of (largely) European researchers (several from EU OntoKnowledge project)
- Based on **frame-based KR languages**
- Strong emphasis on formal rigour
- Semantics in terms of **description logics**
- RDFS based syntax
A Brief History of OWL: DAML-ONT

- DAML: Darpa Agent Markup Language
- Developed by DARPA DAML Program
  - Largely US based researchers
- Extended RDFS with constructors from OO and frame-based languages
- Rather weak semantic specification
  - Problems with machine interpretation
  - Problems with human interpretation
A Brief History of OWL: DAML+OIL

- Merging of DAML-ONT and OIL
- Basically a DL with an RDFS-based syntax
- Development carried out by “Joint EU/US Committee on Agent Markup Languages”
- Extends (“DL subset” of) RDF
- Submitted to W3C as basis for standardisation
  - Web-Ontology (WebOnt)
  - Working Group formed
A Brief History of OWL: OWL

- W3C Recommendation (February 2004)
- Based on March 2001 DAML+OIL specification
- Well defined RDF/XML serializations
- Formal semantics
  - First order logic
  - Relationship with RDF
- Comprehensive test cases for tools/implementations
- Growing industrial take up
OWL 2

- An extension of OWL
  - Addressed deficiencies identified by users and developers (at OWLED workshop)
- Based on more expressive DL subset: SROIQ
- W3C working group chartered
  - Became W3C recommendation Oct. 2009
- Supported by popular OWL tools
  - Protégé, TopBraid, FaCT++, Pellet, ...
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Ontology and Data

- Philosophy: **Ontologies** are models of what exists in the world (kinds of things, relations, events, properties, etc.)
  - Information systems: a schema for info. or data
  - KR languages: model of classes & relations/properties & associated axioms, e.g., subPropertyOf is transitive

- Data is information about individual instances expressed with terms in the ontology
  - Some instances might be considered part of the ontology (e.g., God, George Washington, Baltimore)
Ontology languages let users write explicit, formal conceptualizations of domain models

Requirements:

- well-defined syntax
- efficient reasoning support
- formal semantics
- sufficient expressive power
- convenience of expression
Always a tradeoff between expressive power and efficient reasoning support

The richer the language, the more inefficient the reasoning support becomes (in general)

Reasoning can be *undecidable* or semi-decidable and even if decidable can be exponentially hard

We need a compromise between:
- Language supported by reasonably efficient reasoners
- Language that can express large classes of ontologies and knowledge
Kinds of Reasoning about Knowledge

- **Class membership**
  
  If $x$ is an instance of a class $C$, and $C$ is a subclass of $D$, then we can infer that $x$ is an instance of $D$

- **Equivalence of classes**
  
  If class $A$ is equivalent to class $B$, and class $B$ is equivalent to class $C$, then $A$ is equivalent to $C$, too

- **Consistency**
  
  - $X$ instance of classes $A$ and $B$, but $A$ and $B$ are disjoint
  - This is an indication of an error in the ontology or data

- **Classification**
  
  Certain property-value pairs are a sufficient condition for membership in a class $A$; if an individual $x$ satisfies such conditions, we can conclude that $x$ must be an instance of $A$
Uses for Reasoning

Reasoning support is important for

- Deriving new relations and properties
- Automatically classifying instances in classes
- Checking consistency of ontology and knowledge
- checking for unintended relationships between classes

Checks like these are valuable for

- designing large ontologies, where multiple authors are involved
- integrating and sharing ontologies from various sources
Reasoning Support for OWL

- Semantics is a prerequisite for reasoning support
- Formal semantics and reasoning support usually provided by
  - mapping an ontology language to known logical formalism
  - using automated reasoners that already exist for those formalisms
- OWL is (partially) mapped to a description logic

DLs are a subset of logic for which efficient reasoning support is possible
RDFS’s Expressive Power Limitations

- **Local scope of properties**
  - `rdfs:range` defines range of a property (e.g., eats) for all instances of a class
  - In RDF Schema we can’t declare range restrictions that apply to only some
  - E.g., animals eat living_things but cows only eat plants
  - :eat rdfs:domain :animal; range :living_thing
  - :eat rdfs:domain :cow; range :plant
RDFS’s Expressive Power Limitations

- **Disjointness of classes**
  - Sometimes we wish to say that classes are disjoint (e.g. male and female)

- **Boolean combinations of classes**
  - Sometimes we want to define new classes by combining other classes using union, intersection, and complement
  - E.g., **person** equals disjoint union of **male** and **female** classes
  - E.g., weekdays equals set {[:Monday, ... :Sunday]}
RDFS’s Expressive Power Limitations

- **Cardinality restrictions**
  - E.g., a person has **exactly two** parents, a course is taught by **at least one** lecturer

- **Special characteristics of properties**
  - Transitive property (like “greater than”)
  - Unique property (like “is mother of”)
  - A property is the inverse of another property (like “eats” and “is eaten by”)
Combining OWL with RDF Schema

- Ideally, OWL would extend RDF Schema
  - Consistent with the layered architecture of the Semantic Web
- **But** simply extending RDF Schema works against obtaining expressive power and efficient reasoning
  - Combining RDF Schema with logic leads to uncontrollable computational properties
- OWL uses RDF and most of RDFS
Three Species of OWL 1

- 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 Full

- It uses all the OWL languages primitives
- It allows the combination of these primitives in arbitrary ways with RDF and RDF Schema
- OWL Full is fully upward-compatible with RDF, both syntactically and semantically
- OWL Full is so powerful that it’s undecidable
  - No complete reasoning support
Soundness and completeness

- A sound reasoner only makes conclusions that logically follow from the input, i.e., all of its conclusions are correct
  - We typically require our reasoners to be sound

- A complete reasoner can make all conclusions that logically follow from the input
  - We cannot guarantee complete reasoners for full FOL and many subsets
  - So, we can’t do it for OWL Full
OWL DL

- OWL DL (Description Logic) is a sublanguage of OWL Full that restricts application of the constructors from OWL and RDF
  - Application of OWL’s constructors to each other is disallowed
  - It corresponds to a well studied description logic
- OWL DL permits efficient reasoning support
- **But** we lose full compatibility with RDF
  - Not every RDF document is a legal OWL DL document
  - Every legal OWL DL document is a legal RDF document
OWL Lite

- An even further restriction limits OWL DL to a subset of the language constructors
  - E.g., OWL Lite excludes enumerated classes, disjointness statements, and arbitrary cardinality
- The advantage of this is a language that is easier to
  - grasp, for users
  - implement, for tool builders
- The disadvantage is restricted expressivity
Upward Compatibility for OWL Species

- Every legal OWL Lite ontology is a legal OWL DL ontology
- Every legal OWL DL ontology is a legal OWL Full ontology
- Every valid OWL Lite conclusion is a valid OWL DL conclusion
- Every valid OWL DL conclusion is a valid OWL Full conclusion
All varieties of OWL use RDF for their syntax.

Instances are declared as in RDF, using RDF descriptions.

Typing information

OWL constructors are specialisations of their RDF counterparts.
Semantic Web design aims at downward compatibility with corresponding reuse of software across the various layers.

The advantage of full downward compatibility for OWL is only achieved for OWL Full, at the cost of computational intractability.
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OWL builds on RDF and uses RDF’s serializations

Other syntactic forms for OWL have also been defined:

- Alternative, more readable serializations
OWL documents are RDF documents

and start with a typical declaration of namespaces

The W3C recommendation for owl has the namespace http://www.w3.org/2002/07/owl#
owl:Ontology

<> a owl:Ontology ;
  rdfs:comment "Example OWL ontology" ;
  owl:priorVersion <http://example.org/uni-ns-old> ;
  owl:imports <http://example.org/persons> ;
  rdfs:label "University Ontology" .

- **owl:imports**, a transitive property, indicates that the document commits to all of the terms as defined in its target

- **owl:priorVersion** points to an earlier version of this document
OWL Classes

:AssociateProfessor a owl:Class ;
  owl:disjointWith :Professor,
  :AssistantProfessor .

- Classes are defined using **owl:Class**
- **owl:Class** is a subclass of **rdfs:Class**
- Owl:Class is disjoint with datatypes (aka literals)
- Disjointness is defined using **owl:disjointWith**
  - Two disjoint classes are can share no instances
Another Example

:Man rdfs:subClassOf foaf:Person .
:Woman rdfs:subClassOf foaf:Person .
:Man owl:disjointWith :Woman .

Questions:
- Is :Man an rdfs:Class or a owl:Class?
- Why don’t we need to assert that :Man is some kind of class?
- Do we need to assert the disjointness both ways?
- What happens of we assert :bob a :Man; a :Woman?
Separate Objects & Datatypes?

- Philosophical reasons:
  - Datatypes structured by *built-in predicates*
  - Inappropriate to form new datatypes using ontology language

- Practical reasons:
  - Note: Java does this, distinguishing classes from primitive datatypes
  - Ontology language remains *simple and compact*
  - *Semantic integrity* of ontology language not compromised
  - Implementability not compromised — can use hybrid reasoner

- Only need sound and complete decision procedure for:
  \[ d^{I_1} \land \ldots \land d^{I_n}, \text{ where } d \text{ is a (possibly negated) datatype} \]
OWL Classes

:Faculty a owl:Class;
  owl:equivalentClass :AcademicStaffMember .

- **owl:equivalentClass** asserts two classes are equivalent
  - Each must have the same members

- **owl:Thing** is the most general class, which contains everything
  - i.e., every owl class is rdfs:subClassOf owl:Thing

- **owl:Nothing** is the empty class
  - i.e., owl:NoThing is rdf:subClassOf every owl class
OWL Properties

- OWL has two kinds of properties
- **Object properties** relate objects to other objects
  - owl:ObjectProperty, e.g. is-TaughtBy, supervises
- **Data type properties** relate objects to datatype values
  - owl:DatatypeProperty, e.g. phone, title, age, ...
- These were made separate to make it easier to create sound and complete reasoners
**Datatype Properties**

- OWL uses XML Schema data types, exploiting the layered architecture of the Semantic Web.

```plaintext
:age a owl:DatatypeProperty;
  rdfs:domain foaf:Person;
  rdfs:range xsd:nonNegativeInteger .
```
Typically user-defined data types

:isTaughtBy a owl:ObjectProperty;
  rdfs:domain :course;
  rdfs:range :AcademicStaffMember;
  rdfs:subPropertyOf :involves .
Inverse Properties

:teaches a owl:ObjectProperty;
  rdfs:range :course;
  rdfs:domain :AcademicStaffMember;
  owl:inverseOf :isTaughtBy.

Or just

:teaches owl:inverseOf :isTaughtBy.

A partial list of axioms:

  owl:inverseOf rdfs:domain owl:ObjectProperty;
  rdfs:range owl:ObjectProperty;
  a owl:SymmetricProperty.

Equivalent Properties

:lecturesIn owl:equivalentProperty :teaches .

- Two properties have the same property extension

- Axioms
  
  \[ \{ \ ?A \text{ rdfs:subPropertyOf } \ ?B. \ 
  \ ?B \text{ rdfs:subPropertyOf } \ ?A. \} \ 
  \leftrightarrow \{ \ ?A \text{ owl:equivalentProperty } \ ?B. \}. \]
Declare that class C satisfies certain conditions
  – All instances of C satisfy the conditions

This is equivalent to saying that C is subclass of a class C', where C' collects all objects that satisfy the conditions (C' can remain anonymous)

Example:
  – People whose sex is male and have at least one child whose sex is female and whose age is six
  – Things with exactly two arms and two legs
**Property Restrictions**

- **owl:Restriction** element describes such a class
- Element has an **owl:onProperty** element and one or more **restriction declarations**
- One type defines **cardinality restrictions**
  
  A Parent must have at least one child

  :Parent rdfs:subClassOf

  [a owl:Restriction;
   owl:onProperty :hasChild;
   owl:minCardinalityQ "1"].
This statement **defines** Parent as any Person who has at least one child

:Parent owl:equivalentClass
  owl:intersectionOf (:Person ,
  [a owl:Restriction;
   owl:onProperty :hasChild;
   owl:minCardinalityQ "1"]))
Other restriction types defines restrictions on the kinds of values the property may take

- `owl:allValuesFrom` specifies universal quantification
- `owl:hasValue` specifies a specific value
- `owl:someValuesFrom` specifies existential quantification
Describe a class where all of the values of a property match some requirement

E.g., Math courses taught by professors.

[a :mathCourse,
  [a owl:Restriction;
    owl:onProperty :isTaughtBy;
    owl:allValuesFrom :Professor] ].
foaf:Person a owl:Class;
  rdfs:subClassOf
    [ a owl:Restriction;
      owl:allValuesFrom foaf:Person;
      owl:onProperty bio:offspring ] .
Offspring of people are people

foaf:Person a owl:Class;
  rdfs:subClassOf
    [ a owl:Restriction;
      owl:allValuesFrom foaf:Person;
      owl:onProperty bio:offspring ] .

:john a foaf:Person; bio:offspring :mary
<foaf:Person> rdfs:subClassOf
  [owl:allValuesFrom <foaf:Person>;
    owl:onProperty <bio:offspring>].

:bio:offspring rdfs:domain :animal;
    rdfs:range :animal.

:alice a foaf:Person;
    bio:offspring :bob.

:carol a foaf:Person.
:don bio:offspring :carol.

...
<foaf:Person> rdfs:subClassOf
  [owl:allValuesFrom <foaf:Person>;
   owl:onProperty <bio:sprungFrom>]
.

bio:sprungFrom rdfs:domain :animal;
  rdfs:range :animal;
  owl:inverse bio:offspring.

:carol a foaf:Person.
:don bio:offspring :carol.
???
• Describe a class with a particular value for a property
• E.g., Math courses taught by Professor Longhair

<!-- Math courses taught by #949352 -->
<owl:Class>
  <rdfs:subClassOf rdf:resource="#mathCourse"/>
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#isTaughtBy"/>
      <owl:hasValue rdf:resource="#949352"/>
    </owl:Restriction>
  </rdfs:subClassOf>
</owl:Class>
owl:hasValue

- Describe a class with a particular value for a property
- E.g., Math courses taught by Professor Longhair

Math courses taught by :longhair
[ rdfs:subclassOf :mathCourse;
  [ a owl:restriction;
    owl:onProperty :isTaughtBy;
    owl:hasValue :longhair ] ].

Questions:
- Does this say all math courses are taught by :longhair?
- Does it say that there are some courses taught by :longhair?
- Can all classes, however defined, by paraphrased by a noun phrase in English?
A typical example

:Male owl:equivalentClass
owl:intersectionOf
(:Person,
 [a owl:Restriction;
 owl:onProperty :sex;
 owl:hasValue "male"] ).
What follows?

:ed a :male?

???

:frank a foaf:Person; :sex "male".

???

:gerry a foaf:Person; :sex "male"; :sex "female" .
Describe class requiring it to have *at least one value* for a property matching a description.

E.g., Academic staff members who teach an undergraduate course.

```
<owl:Class rdf:about="#academicStaffMember">
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#teaches"/>
      <owl:someValuesFrom rdf:resource="#undergraduateCourse"/>
    </owl:Restriction>
  </rdfs:subClassOf>
</owl:Class>
```
Describe class requiring it to have *at least one value* for a property matching a description

E.g., Academic staff members who teach an undergraduate course

```
[ a :academicStaffMember;
  a [owl:onProperty :teaches;
      owl:someValuesFrom :undergraduateCourse] ]
```
Cardinality Restrictions

- We can specify minimum and maximum number using `owl:minCardinality & owl:maxCardinality`
  - Courses with fewer than 10 students
  - Courses with between 10 and 100 students
  - Courses with more than 100 students

- Can specify a precise number by using the same minimum and maximum number
  - Courses with exactly seven students

- For convenience, OWL offers also `owl:cardinality`
  - E.g., exactly N
Cardinality Restrictions

E.g. courses taught be at least two people

<owl:Class rdf:about="#course">
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#isTaughtBy"/>
      <owl:minCardinality rdf:datatype="&xsd;nonNegativeInteger">
        2
      </owl:minCardinality>
    </owl:Restriction>
  </rdfs:subClassOf>
</owl:Class>
E.g. courses taught be at least two people

[ a owl:Restriction;
  owl:onProperty :isTaughtBy;
  owl:minCardinality "2"^^xsd:nonNegativeInteger ] .
<owl:Class rdf:ID="Parent">
  <owl:equivalentClass>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#hasChild" />
      <owl:minCardinality rdf:datatype="&xsd;nonNegativeInteger">1</owl:minCardinality>
    </owl:Restriction>
  </owl:equivalentClass>
</owl:Class>
What does this say?

:Parent owl:equivalentClass

[a owl:Restriction;
 owl:onProperty :hasChild;
 owl:minCardinality "1"^^xsd:integer] .

Questions:
- Must parents be humans?
- Must their children be humans?
The parent class is equivalent to the class of things that have at least one child

\[
\text{All}(x): \text{Parent}(x) \iff \text{Exists}(y) \text{ hasChild}(x, y)
\]

If hasChild is defined as having Person as it’s domain, then Parents are also people.
Special Properties

• **owl:TransitiveProperty** (transitive property)
  – E.g. “has better grade than”, “is ancestor of”

• **owl:SymmetricProperty** (symmetry)
  – E.g. “has same grade as”, “is sibling of”

• **owl:FunctionalProperty** defines a property that has at most one value for each object
  – E.g. “age”, “height”, “directSupervisor”

• **owl:InverseFunctionalProperty** defines a property for which two different objects cannot have the same value
hasSameGradeAs
   a owl:ObjectProperty, owl:SymmetricProperty;
   rdfs:domain student;
   rdfs:range student .
We can combine classes using Boolean operations (union, intersection, complement).

Negation is introduced by the `complementOf`, e.g., courses not taught be staffMembers

```
[ a :course,
  owl:Restriction;
  owl:onProperty :teaches;
  owl:allValuesFrom [ a owl:Class;
             owl:complementOf :staffMember ]
].
```
The new class is not a subclass of the union, but rather equal to the union
- We have stated an equivalence of classes
E.g., university people is the union of staffMembers and Students

:peopleAtUni
  owl:equivalentClass
    owl:unionOf (:staffMember :student) .
Boolean Combinations

E.g., CS faculty is the intersection of faculty and things that belongTo the CS Department.

:facultyInCS owl:equivalentClass
owl:intersectionOf
  (:faculty
   [ a owl:Restriction;
     owl:onProperty :belongsTo;
     owl:hasValue :CSDepartment ]
  ).
Nesting of Boolean Operators

E.g., administrative staff are staff members who are not faculty or technical staff members

:adminStaff owl:equivalentClass
    owl:intersectionOf
    (:staffMember
     [a owl:Class;
     owl:complementOf [a owl:Class;
     owl:equivalentClass
     owl:unionOf (:faculty :techSupportStaff)])
}
Enumerations with owl:oneOf

- *E.g., a thing that is either Monday, Tuesday, ...*

[a owl:Class;
 owl:oneOf (:Monday
 :Tuesday
 :Wednesday
 :Thursday
 :Friday
 :Saturday
 :Sunday) ]
Declaring Instances

Instances of OWL classes are declared as in RDF

:john
    a :academicStaffMember;
    uni:age 39^^xsd:integer .
No Unique-Names Assumption

- OWL does not adopt the unique-names assumption of database systems
  - That two instances have a different name or ID does not imply that they are different individuals

- Suppose we state that each course is taught by at most one staff member, and that a given course is taught by #949318 and is taught by #949352
  - An OWL reasoner does not flag an error
  - Instead it infers that the two resources are equal
Distinct Objects

To ensure that different individuals are indeed recognized as such, we must explicitly assert their inequality:

:john owl:differentFrom :mary.
Distinct Objects

OWL provides a shorthand notation to assert the pairwise inequality of all individuals in a given list:

[a owl:allDifferent;
 owl:distinctMembers (:alice :bob :carol :don) ].
Data Types in OWL

- XML Schema provides a mechanism to construct user-defined data types
  - E.g., the data type of `adultAge` includes all integers greater than 18

- Such derived data types can’t be used in OWL
  - The OWL reference document lists all the XML Schema data types that can be used
  - These include the most frequently used types such as `string`, `integer`, `Boolean`, `time`, and `date`. 
Versioning Information

- **owl:priorVersion** indicates earlier versions of the current ontology
  - No formal meaning, can be exploited for ontology management

- **owl:versionInfo** generally contains a string giving information about the current version, e.g. keywords
Versioning Information

- **owl:backwardCompatibleWith** contains a reference to another ontology
  - All identifiers from the previous version have the same intended interpretations in the new version
  - Thus documents can be safely changed to commit to the new version

- **owl:incompatibleWith** says that the containing ontology is a later version of the referenced ontology but is not backward compatible with it
Combination of Features in OWL Profiles

- In different OWL languages there are different sets of restrictions regarding the application of features.
- In **OWL Full**, all the language constructors may be used in any combination as long as the result is legal RDF.
- OWL DL removes or restricts some features to ensure that complete reasoning is *tractable* or to make reasoning implementations easier.
Restriction of Features in OWL DL

- **Vocabulary partitioning**
  - Any resource is allowed to be only a class, a data type, a data type property, an object property, an individual, a data value, or part of the built-in vocabulary, and not more than one of these.

- **Explicit typing**
  - The partitioning of all resources must be stated explicitly (e.g. a class must be declared if used in conjunction with rdfs:subClassOf).
**Property Separation**

- The set of object properties and data type properties are disjoint
- Therefore the following can never be specified for data type properties:
  - `owl:inverseOf`
  - `owl:FunctionalProperty`
  - `owl:InverseFunctionalProperty`
  - `owl:SymmetricProperty`
Restriction of Features in OWL DL

- **No transitive cardinality restrictions**
  - No cardinality restrictions may be placed on transitive properties
  - e.g., people with more than 5 ancestors

- **Restricted anonymous classes**
  Anonymous classes are only allowed to occur as:
  - the domain and range of either `owl:equivalentClass` or `owl:disjointWith`
  - the range (but not the domain) of `rdfs:subClassOf`
Restriction of Features in OWL Lite

- Restrictions of OWL DL and more
- `owl:oneOf`, `owl:disjointWith`, `owl:unionOf`, `owl:complementOf`, `owl:hasValue` not allowed
- Cardinality statements (minimal, maximal, exact cardinality) can only be made on values 0 or 1
- `owl:equivalentClass` statements can no longer be made between anonymous classes but only between class identifiers
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African Wildlife Ontology: Classes

animal
  
herbivore
giraffe

  carnivore
  
lion

plant
tree
Branches are parts of trees
African Wildlife: Properties

<owl:TransitiveProperty rdf:ID="is-part-of"/>

<owl:ObjectProperty rdf:ID="eats">
  <rdfs:domain rdf:resource="#animal"/>
</owl:ObjectProperty>

<owl:ObjectProperty rdf:ID="eaten-by">
  <owl:inverseOf rdf:resource="#eats"/>
</owl:ObjectProperty>
African Wildlife: Plants and Trees

<owl:Class rdf:ID="plant">
  <rdfs:comment>Plants are disjoint from animals.</rdfs:comment>
  <owl:disjointWith="#animal"/>
</owl:Class>

<owl:Class rdf:ID="tree">
  <rdfs:comment>Trees are a type of plant.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#plant"/>
</owl:Class>
Branches are parts of trees.
African Wildlife: Leaves

<owl:Class rdf:ID="leaf">
  <rdfs:comment>Leaves are parts of branches.</rdfs:comment>
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#is-part-of"/>
      <owl:allValuesFrom rdf:resource="#branch"/>
    </owl:Restriction>
  </rdfs:subClassOf>
</owl:Class>
African Wildlife: Carnivores

<owl:Class rdf:ID="carnivore">
  <rdfs:comment>Carnivores are exactly those animals that eat also animals.</rdfs:comment>
  <owl:intersectionOf rdf:parseType="Collection">
    <owl:Class rdf:about="#animal"/>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#eats"/>
      <owl:someValuesFrom rdf:resource="#animal"/>
    </owl:Restriction>
  </owl:intersectionOf>
</owl:Class>
How can we define Herbivores?
African Wildlife: Herbivores

Here is a start

:herbivore a owl:Class;
  rdfs:comment "Herbivores are exactly those animals that eat only plants or parts of plants" .
African Wildlife: Herbivores

:herbivore owl:equivalentClass
  [a owl:Class;
   owl:intersectionOf
   (:animal
    [a owl:Restriction
     owl:onProperty :eats;
     owl:allValuesFrom
     [a owl:Class;
      owl:equivalentClass
      owl:unionOf
      (:plant
       [a owl:Restriction;
        owl:onProperty :is_part_of;
        owl:allValuesFrom :plant])))])
<owl:Class rdf:ID="herbivore">
<owl:intersectionOf rdf:parseType="Collection">
  <owl:Class rdf=about="#animal"/>
  <owl:Restriction>
    <owl:onProperty rdf:resource="#eats"/>
    <owl:allValuesFrom>
      <owl:Class>
        <owl:unionOf rdf:parseType="Collection">
          <owl:Class rdf:resource="plant"/>
          <owl:Restriction>
            <owl:onProperty rdf:resource="#is_part_of"/>
            <owl:allValuesFrom rdf:resource="#plant"/>
          </owl:Restriction>
        </owl:unionOf>
      </owl:Class>
    </owl:allValuesFrom>
  </owl:Restriction>
</owl:intersectionOf>
</owl:Class>
Giraffes are herbivores, and they eat only leaves.
Lions are animals that eat only herbivores.

```
<owl:Class rdf:ID="lion">
  <rdfs:comment>Lions are animals that eat only herbivores.</rdfs:comment>
  <rdfs:subClassOf rdf:type="#carnivore"/>
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#eats"/>
      <owl:allValuesFrom rdf:resource="#herbivore"/>
    </owl:Restriction>
  </rdfs:subClassOf>
</owl:Class>
```
Plants eaten both by herbivores and carnivores

[? ??????????????????]
<owl:Class rdf:ID="tasty-plant">
  <rdfs:subClassOf rdf:resource="#plant"/>
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#eaten_by"/>
      <owl:someValuesFrom> <owl:Class rdf:about="#herbivore"/>
      </owl:someValuefrom>
    </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#eaten_by"/>
      <owl:someValuesFrom> <owl:Class rdf:about="#carnivore"/>
      </owl:someValuefrom>
    </owl:Restriction>
  </rdfs:subClassOf>
</owl:Class>
Printer Ontology – Class Hierarchy
Products form a class. Printing and digital imaging devices form a subclass of products.

Device

Printer Ontology – Products and Devices
Printer Ontology – HP Products

<owl:Class rdf:ID="hpProduct">
  <owl:intersectionOf>
    <owl:Class rdf:about="#product"/>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#manufactured-by"/>
      <owl:hasValue>
        <xsd:string rdf:value="Hewlett Packard"/>
      </owl:hasValue>
    </owl:Restriction>
  </owl:intersectionOf>
</owl:Class>
**Printer Ontology – Printers & Personal Printers**

```xml
<owl:Class rdf:ID="printer">
  <rdfs:comment>Printers are printing and digital imaging devices.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#padid"/>
</owl:Class>

<owl:Class rdf:ID="personalPrinter">
  <rdfs:comment>Printers for personal use form a subclass of printers.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#printer"/>
</owl:Class>
```
HP LaserJet 1100se Printers

<owl:Class rdf:ID="1100se">
   <rdfs:comment>1100se printers belong to the 1100 series and cost $450.</rdfs:comment>
   <rdfs:subClassOf rdf:resource="#1100series"/>
   <rdfs:subClassOf>
      <owl:Restriction>
         <owl:onProperty rdf:resource="#price"/>
         <owl:hasValue><xsd:integer rdf:value="450"/></owl:hasValue>
      </owl:Restriction>
   </rdfs:subClassOf>
</owl:Class>
A Printer Ontology – Properties

<owl:DatatypeProperty rdf:ID="manufactured-by">
    <rdfs:domain rdf:resource="#product"/>
    <rdfs:range rdf:resource="&xsd:string"/>
</owl:DatatypeProperty>

<owl:DatatypeProperty rdf:ID="printingTechnology">
    <rdfs:domain rdf:resource="#printer"/>
    <rdfs:range rdf:resource="&xsd:string"/>
</owl:DatatypeProperty>
Outline

1. A bit of history
2. Basic Ideas of OWL
3. The OWL Language
4. Examples
5. The OWL Namespace
6. OWL 2
We present a part of the definition of OWL in terms of itself.

The following captures some of OWL’s meaning in OWL:
- It does not capture the entire semantics
- A separate semantic specification is necessary

The URI of the OWL definition is defined as the default namespace.
The class of all OWL classes is itself a subclass of the class of all RDF Schema classes:

```xml
<rdfs:Class rdf:ID="Class">
  <rdfs:label>Class</rdfs:label>
  <rdfs:subClassOf rdf:resource="&rdfs;Class"/>
</rdfs:Class>
```
• **Thing** is most general object class in OWL

• **Nothing** is most specific class: the empty object class

• The following relationships hold:

\[
\text{Thing} = \text{Nothing} \cup \text{Nothing}
\]

\[
\text{Nothing} = \text{Thing} = \text{Nothing} \cup \text{Nothing} = \text{Nothing} \cap \text{Nothing} = \emptyset
\]
Metaclasses – Thing and Nothing

<Class rdf:ID="Thing">
  <rdfs:label>Thing</rdfs:label>
  <unionOf rdf:parseType="Collection">
    <Class rdf:about="#Nothing"/>
    <Class>
      <complementOf rdf:resource="#Nothing"/>
    </Class>
  </unionOf>
</Class>

<Class rdf:ID="Nothing">
  <rdfs:label>Nothing</rdfs:label>
  <complementOf rdf:resource="#Thing"/>
</Class>
Class and Property Equivalences

<rdf:Property rdf:ID="EquivalentClass">
  <rdfs:label>EquivalentClass</rdfs:label>
  <rdfs:subPropertyOf rdf:resource="&rdfs;subClassOf"/>
  <rdfs:domain rdf:resource="#Class"/>
  <rdfs:range rdf:resource="#Class"/>
</rdf:Property>

<rdf:Property rdf:ID="EquivalentProperty">
  <rdfs:label>EquivalentProperty</rdfs:label>
  <rdfs:subPropertyOf rdf:resource="&rdfs;subPropertyOf"/>
</rdf:Property>
Class Disjointness

<rdf:Property rdf:ID="disjointWith">
   <rdfs:label>disjointWith</rdfs:label>
   <rdfs:domain rdf:resource="#Class" />
   <rdfs:range rdf:resource="#Class" />
</rdf:Property>
Equality and Inequality

- Equality and inequality can be stated between arbitrary things
  - In OWL Full this statement can also be applied to classes
- Properties `sameIndividualAs`, `sameAs` and `differentFrom`
Equality and Inequality

```xml
<rdf:Property rdf:ID="sameIndividualAs">
  <rdfs:domain rdf:resource="#Thing"/>
  <rdfs:range rdf:resource="#Thing"/>
</rdf:Property>

<rdf:Property rdf:ID="sameAs">
  <EquivalentProperty rdf:resource="#sameIndividualAs"/>
</rdf:Property>
```
Build a class from a list, assumed to be a list of other class expressions

```xml
<rdf:Property rdf:ID="unionOf">
    <rdfs:domain rdf:resource="#Class"/>
    <rdfs:range rdf:resource="&rdf;List"/>
</rdf:Property>
```
Restrictions in OWL define the class of those objects that satisfy some attached conditions.

```xml
<rdfs:Class rdf:ID="Restriction">
  <rdfs:label>Restriction</rdfs:label>
  <rdfs:subClassOf rdf:resource="#Class"/>
</rdfs:Class>
```
All the following properties (onProperty, allValuesFrom, minCardinality, etc.) are only allowed to occur within a restriction definition.

- Their domain is owl:Restriction, but they differ with respect to their range.
<rdf:Property rdf:ID="onProperty">
  <rdfs:label>onProperty</rdfs:label>
  <rdfs:domain rdf:resource="#Restriction"/>
  <rdfs:range rdf:resource="&rdf;Property"/>
</rdf:Property>

<rdf:Property rdf:ID="allValuesFrom">
  <rdfs:label>allValuesFrom</rdfs:label>
  <rdfs:domain rdf:resource="#Restriction"/>
  <rdfs:range rdf:resource="&rdfs;Class"/>
</rdf:Property>
Restriction Properties

<rdf:Property rdf:ID="hasValue">
  <rdfs:label>hasValue</rdfs:label>
  <rdfs:domain rdf:resource="#Restriction"/>
</rdf:Property>

<rdf:Property rdf:ID="minCardinality">
  <rdfs:label>minCardinality</rdfs:label>
  <rdfs:domain rdf:resource="#Restriction"/>
  <rdfs:range rdf:resource="&xsd;nonNegativeInteger"/>
</rdf:Property>
Properties

- **owl:ObjectProperty** and **owl:DatatypeProperty** are special cases of **rdf:Property**

```xml
<rdfs:Class rdf:ID="ObjectProperty">
  <rdfs:label>ObjectProperty</rdfs:label>
  <rdfs:subClassOf rdf:resource="&rdf:Property;"/>
</rdfs:Class>
```
Properties

Symmetric, functional and inverse functional properties can only be applied to object properties

<rdfs:Class rdf:ID="TransitiveProperty">
    <rdfs:label>TransitiveProperty</rdfs:label>
    <rdfs:subClassOf rdf:resource="#ObjectProperty"/>
</rdfs:Class>
Properties

owl:inverseOf relates two object properties

<rdf:Property rdf:ID="inverseOf">
    <rdfs:label>inverseOf</rdfs:label>
    <rdfs:domain rdf:resource="#ObjectProperty"/>
    <rdfs:range rdf:resource="#ObjectProperty"/>
</rdf:Property>
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Extensions of OWL

- Modules and Imports
- Defaults
- Closed World Assumption
- Unique Names Assumption
- Procedural Attachments
- Rules for Property Chaining
The importing facility of OWL is very trivial:
- It only allows importing of an entire ontology, not parts of it

Modules in programming languages based on **information hiding**: state functionality, hide implementation details
- Open question how to define appropriate module mechanism for Web ontology languages
Many practical knowledge representation systems allow inherited values to be overridden by more specific classes in the hierarchy
- treat inherited values as defaults

No consensus has been reached on the right formalization for the nonmonotonic behaviour of default values
Closed World Assumption

- OWL currently adopts the **open-world assumption**:
  - A statement cannot be assumed true on the basis of a failure to prove it
  - On the huge and only partially knowable WWW, this is a correct assumption

- **Closed-world assumption**: a statement is true when its negation cannot be proved
  - tied to the notion of defaults, leads to nonmonotonic behaviour
Unique Names Assumption

- Typical database applications assume that individuals with different names are indeed different individuals.
- OWL follows the usual logical paradigm where this is not the case.
  - Plausible on the WWW.
- One may want to indicate portions of the ontology for which the assumption does or does not hold.
Procedural Attachments

- A common concept in knowledge representation is to define the meaning of a term by attaching a piece of code to be executed for computing the meaning of the term
  - Not through explicit definitions in the language
- Although widely used, this concept does not lend itself very well to integration in a system with a formal semantics, and it has not been included in OWL
Rules for Property Chaining

- OWL does not allow the composition of properties for reasons of decidability.
- In many applications this is a useful operation.
- One may want to define properties as general rules (Horn or otherwise) over other properties.
- Integration of rule-based knowledge representation and DL-style knowledge representation is an area of research.
OWL 2 adds

- Qualified cardinality
  - A hand has five digits, one of which is a thumb and four of which are fingers
- Stronger datatype/range support
- Additional property characteristics
  - E.g., reflexivity
- Role chains
  - E.g., hasParent.hasSibling.hasChild
- A better defined model for punning within DL
  - Allows a term to name both a concept and an individual
- More powerful annotations
Conclusions

- OWL is the proposed standard for Web ontologies
- OWL builds upon RDF and RDF Schema:
  - (XML-based) RDF syntax is used
  - Instances are defined using RDF descriptions
  - Most RDFS modelling primitives are used
- Formal semantics and reasoning support is provided through the mapping of OWL on logics
  - Predicate logic and description logics have been used for this purpose
- While OWL is sufficiently rich to be used in practice, extensions are in the making
  - They will provide further logical features, including rules