Chapter 4

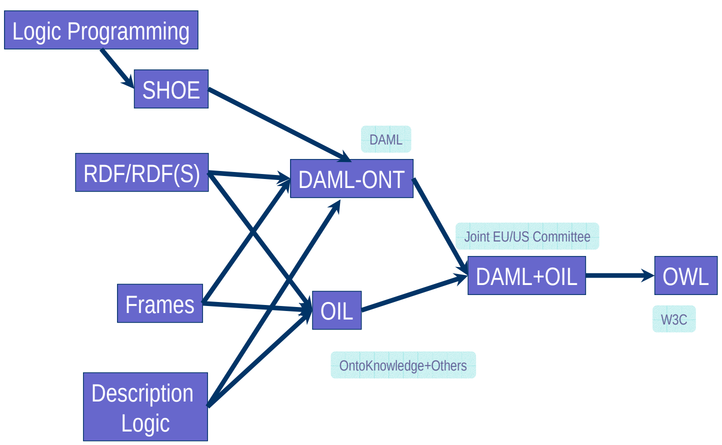
OWL

Based on slides from Grigoris Antoniou and Frank van Harmelen

Outline

1. **A bit of history**
2. Basic Ideas of OWL
3. The OWL Language
4. Examples
5. The OWL Namespace
6. Future Extensions

The OWL Family Tree



A Brief History of OWL: SHOE

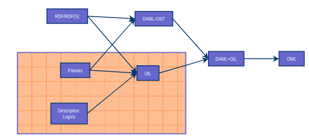
- Simple HTML Ontology Extensions
- Sean Luke, Lee Spector, and David Rager, 1996
  SHOE allows World-Wide Web authors to annotate their pages with ontology-based knowledge about page contents. We present examples showing how the use of SHOE can support a new generation of knowledge-based search and knowledge discovery tools that operate on the World-Wide Web.
- Supported adding "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://www.cs.umd.edu/~helena">
<RELATION "our.employee" FROM="http://www.cs.umd.edu">
```

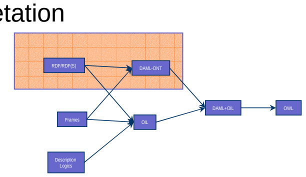
A Brief History of OWL: OIL

- Developed by group of (largely) European researchers (several from EU OntoKnowledge project)
- Based on frame-based language
- Strong emphasis on formal rigour.
- Semantics in terms of Description Logics
- RDFS based syntax



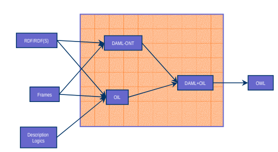
A Brief History of OWL: DAML-ONT

- 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



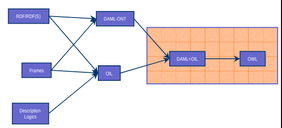
A Brief History of OWL: DAML+OIL

- Merging of DAML-ONT and OIL
- Basically a DL with an RDFS-based syntax.
- Development was 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 largely on the March 2001 DAML+OIL specification
- Well defined RDF/XML serializations
- Formal semantics
  - First Order
  - Relationship with RDF
- Comprehensive test cases for tools/implementations
- Growing industrial take up.



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Requirements for Ontology Languages

- **Ontology languages allow users to write explicit, formal conceptualizations of domain models**
- The main requirements are:
  - a well-defined syntax
  - efficient reasoning support
  - a formal semantics
  - sufficient expressive power
  - convenience of expression

Expressive Power vs Efficient Reasoning

- There is always a tradeoff between expressive power and efficient reasoning support
- The richer the language is, the more inefficient the reasoning support becomes
- Sometimes it crosses the ***noncomputability*** border
- We need a compromise:
  - A language supported by reasonably efficient reasoners
  - A 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
- 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
  - checking the consistency of the ontology and the knowledge
  - checking for unintended relationships between classes
  - automatically classifying instances in classes
- Checks like the preceding ones 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 are usually provided by
  - mapping an ontology language to a known logical formalism
  - using automated reasoners that already exist for those formalisms
- OWL is (partially) mapped on a description logic, and makes use of reasoners such as FaCT, RACER and Pellet
- Description logics are a subset of predicate logic for which efficient reasoning support is possible

RDFS's Expressive Power Limitations

- Local scope of properties
  - **rdfs:range** defines the range of a property (e.g. eats) for all classes
  - In RDF Schema we cannot declare range restrictions that apply to some classes only
  - E.g. we cannot say that cows eat only plants, while other animals may eat meat, too

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 wish to build new classes by combining other classes using union, intersection, and complement
  - E.g. **person** is the disjoint union of the classes **male** and **female**

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 would work against obtaining expressive power and efficient reasoning
  - Combining RDF Schema with logic leads to uncontrollable computational properties

Three Species of OWL

- W3C'sWeb 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 is undecidable
  - No complete (or efficient) reasoning support

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
  - Therefore 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

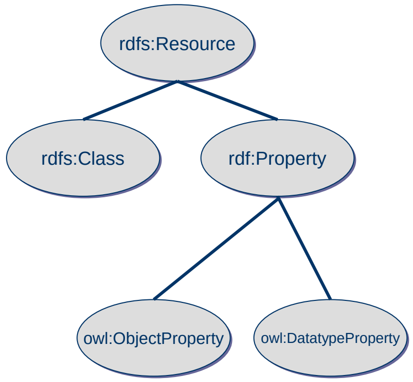
- An even further restriction limits OWL DL to a subset of the language constructors
  - E.g., OWL Lite excludes enumerated classes, disjointness statements, and arbitrary cardinality.
- The advantage of this is a language that is easier to
  - grasp, for users
  - implement, for tool builders
- The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

OWL Compatibility with RDF Schema

- All varieties of OWL use RDF for their syntax
- Instances are declared as in RDF, using RDF descriptions
- and typing information OWL constructors are specialisations of their RDF counterparts



OWL Compatibility with RDF Schema

- 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 Syntactic Varieties

- OWL builds on RDF and uses RDF’s XML-based syntax
- Other syntactic forms for OWL have also been defined:
  - An alternative, more readable XML-based syntax
  - An abstract syntax, that is much more compact and readable than the XML languages
  - A graphic syntax based on the conventions of UML

OWL XML/RDF Syntax: Header

```
<rdf:RDF
   xmlns:owl ="http://www.w3.org/2002/07/owl#"
   xmlns:rdf ="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
   xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
   xmlns:xsd ="http://www.w3.org/2001/  XLMSchema#">
```

- 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

```
<owl:Ontology rdf:about="">
 <rdfs:comment>Example OWL ontology</rdfs:comment>
 <owl:priorVersion rdf:resource="http://www.-
          mydomain.org/uni-ns-old"/>
 <owl:imports rdf:resource="http://www.-mydomain.org/-
    persons"/>
 <rdfs:label>University Ontology</rdfs:label>
</owl: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

```
<owl:Class rdf:about="#associateProfessor">
 <owl:disjointWith rdf:resource="#professor"/>
 <owl:disjointWith  rdf:resource="#assistantProfessor"/>
</owl:Class>
```

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

Why Separate Classes & Datatypes?

- **Philosophical reasons:**
  - Datatypes structured by built-in predicates
  - Not appropriate 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:
      $g^L{}_1$ _ … _ $g^L{}_q$, where g is a (possibly negated) datatype

OWL Classes

```
<owl:Class rdf:ID="faculty">
 <owl:equivalentClass rdf:resource="#academicStaffMember"/>
</owl:Class>
```

- **owl:equivalentClass** defines equivalence of classes
- **owl:Thing** is the most general class, which contains everything
  - i.e., every owl class is rdf:subClassOf owl:Thing
- **owl:Nothing** is the empty class
  - i.e., owl:NoThing is rdf:subClassOf every owl class

OWL Properties

- In OWL there are two kinds of properties
- Object properties relate objects to other objects
  - owl:DatatypeProperty
  - E.g. is-TaughtBy, supervises
- Data type properties relate objects to datatype values
  - owl:ObjectProperty
  - E.g. phone, title, age, etc.

Datatype Properties

- OWL makes use of XML Schema data types, using the layered architecture of the Semantic Web

```
<owl:DatatypeProperty rdf:ID="age">
  <rdfs:range rdf:resource=
       "http://www.w3.org/2001/XLMSchema
       #nonNegativeInteger"/>
  <rdfs:domain rdf:resource="foaf:Person">
</owl:DatatypeProperty>
```

OWL Object Properties

- Typically user-defined data types

```
<owl:ObjectProperty rdf:ID="isTaughtBy">
  <owl:domain rdf:resource="#course"/>
  <owl:range rdf:resource=
      "#academicStaffMember"/>
  <rdfs:subPropertyOf rdf:resource="#involves"/>
</owl:ObjectProperty>
```

Inverse Properties

```
<owl:ObjectProperty rdf:ID="teaches">
  <rdfs:range rdf:resource="#course"/>
  <rdfs:domain rdf:resource=
       "#academicStaffMember"/>
  <owl:inverseOf rdf:resource="#isTaughtBy"/>
</owl:ObjectProperty>
```

- A partial list of axioms

```
owl:inverseOf rdfs:domain owl:ObjectProperty;
  rdfs:range owl:ObjectProperty;
  a owl:SymmetricProperty.
{?P @has owl:inverseOf ?Q. ?S ?P ?O} => {?O ?Q ?S}.
{?P owl:inverseOf ?Q. ?P @has rdfs:domain ?C} => {?Q rdfs:range ?C}.
{?A owl:inverseOf ?C. ?B owl:inverseOf ?C} => {?A rdfs:subPropertyOf ?B}.
```

Equivalent Properties

```
<owl:equivalentProperty
  <owl:ObjectProperty rdf:ID="lecturesIn">
  <owl:equivalentProperty rdf:resource="#teaches"/>
</owl:ObjectProperty>
```

- Two properties have the same property extension
- Axioms

```
{?A rdfs:subPropertyOf ?B. ?B rdfs:subPropertyOf ?A}
  <=> {?A owl:equivalentProperty ?B}.
```

Property Restrictions

- In OWL we can declare that the 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

- The **owl:Restriction** element describes such a class
- This element contains an **owl:onProperty** element and one or more restriction declarations
- One type defines cardinality restrictions (at least one, at most 3,…)
- The other type 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

owl:allValuesFrom

- Describe a class where all of the values of a property match some requirement
- E.g., Math courses taught by professors.

```
<!-- First year courses that are taught by professors -->
<owl:Class rdf:about="#firstYearCourse">
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#isTaughtBy"/>
       <owl:allValuesFrom rdf:resource="#Professor"/>
     </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 #949352 →

<owl:Class rdf:about="#mathCourse">
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource= "#isTaughtBy"/>
      <owl:hasValue rdf:resource= "#949352"/>
```

owl:someValuesFrom

- Describe a class based on a requirement that it must 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>
```

Cardinality Restrictions

- We can specify minimum and maximum number using **owl:minCardinality** and **owl:maxCardinality**
  - Courses with fewer than 10 students
  - Courses with between 10 and 100 students
  - Courses with more than 100 students
- It is possible to 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>
```

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

Special Properties

```
<owl:ObjectProperty rdf:ID="hasSameGradeAs">
        <rdf:type rdf:resource="&owl;TransitiveProperty"/>
        <rdf:type rdf:resource="&owl;SymmetricProperty"/>
        <rdfs:domain rdf:resource="#student"/>
        <rdfs:range rdf:resource="#student"/>
</owl:ObjectProperty>
```

Boolean Combinations

- We can combine classes using Boolean operations (union, intersection, complement)
- Negation is introduced by the complementOf
- *E.g., courses not taught be staffMembers*

```
<owl:Class rdf:about="#course">
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#teaches"/>
      <owl:allValuesFrom>
        <owl:complementOf rdf:resource="#staffMember"/>
      <owl:allValuesFrom>
    </owl:Restriction>
  </rdfs:subClassOf>
</owl:Class>
```

Boolean Combinations

- 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*

```
<owl:Class rdf:ID="peopleAtUni">
  <owl:unionOf rdf:parseType="Collection">
      <owl:Class rdf:about="#staffMember"/>
      <owl:Class rdf:about="#student"/>
  </owl:unionOf>
```

Boolean Combinations

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

```
<owl:Class rdf:ID="facultyInCS">
 <owl:intersectionOf rdf:parseType="Collection">
  <owl:Class rdf:about="#faculty"/>
  <owl:Restriction>
   <owl:onProperty rdf:resource="#belongsTo"/>
   <owl:hasValue rdf:resource="#CSDepartment"/>
  </owl:Restriction>
 </owl:intersectionOf>
</owl:Class>
```

Nesting of Boolean Operators

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

```
<owl:Class rdf:ID="adminStaff">
 <owl:intersectionOf rdf:parseType="Collection">
  <owl:Class rdf:about="#staffMember"/>
  <owl:complementOf>
   <owl:unionOf rdf:parseType="Collection">
    <owl:Class rdf:about="#faculty"/>
    <owl:Class rdf:about="#techSupportStaff"/>
   </owl:unionOf>
  </owl:complementOf>
 </owl:intersectionOf>
</owl:Class>
```

Enumerations with owl:oneOf

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

```
<owl:oneOf rdf:parseType="Collection">
 <owl:Thing rdf:about="#Monday"/>
 <owl:Thing rdf:about="#Tuesday"/>
 <owl:Thing rdf:about="#Wednesday"/>
 <owl:Thing rdf:about="#Thursday"/>
 <owl:Thing rdf:about="#Friday"/>
 <owl:Thing rdf:about="#Saturday"/>
 <owl:Thing rdf:about="#Sunday"/>
</owl:oneOf>
```

Declaring Instances

- Instances of classes are declared as in RDF, as in these examples

```
<rdf:Description rdf:ID="949352">
  <rdf:type rdf:resource="#academicStaffMember"/>
</rdf:Description>
<academicStaffMember rdf:ID="949352">
  <uni:age rdf:datatype="&xsd;integer">
    39
  <uni:age>
</academicStaffMember>
```

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:

```
<lecturer rdf:about="949318">
  <owl:differentFrom rdf:resource="949352"/>
</lecturer>
```

Distinct Objects

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

```
<owl:allDifferent>
  <owl:distinctMembers rdf:parseType="Collection">
    <lecturer rdf:about="949318"/>
    <lecturer rdf:about="949352"/>
    <lecturer rdf:about="949111"/>
  </owl:distinctMembers>
</owl:allDifferent>
```

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 cannot 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** indicates that the containing ontology is a later version of the referenced ontology but is not backward compatible with it

Combination of Features

- 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

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**)

Restriction of Features in OWL DL

- 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

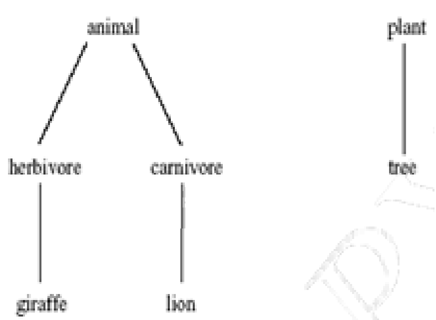
- Restrictions of OWL DL and more
- **owl:oneOf**, **owl:disjointWith**, **owl:unionOf**, **owl:complementOf** and **owl:hasValue** are not allowed
- Cardinality statements (minimal, maximal, and exact cardinality) can only be made on the values 0 or 1
- **owl:equivalentClass** statements can no longer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

Inheritance in Class Hierarchies

- Range restriction: **Courses must be taught by academic staff members only**
- Ben Bitdiddle is a professor
- He **inherits** the ability to teach from the class of academic staff members
- This is done in RDF Schema by fixing the semantics of "is a subclass of"
  - It is not up to an application (RDF processing software) to interpret "is a subclass of

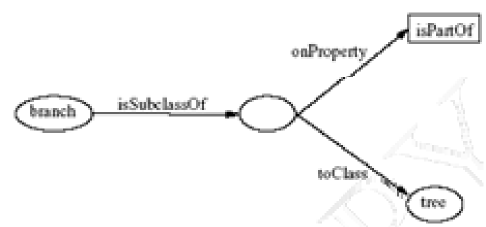
Outline

African Wildlife Ontology: Classes



African Wildlife: Schematic Representation

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>
```

An African Wildlife: Branches

```
<owl:Class rdf:ID="branch">
    <rdfs:comment>Branches are parts of trees.
    </rdfs:comment>
    <rdfs:subClassOf>
        <owl:Restriction>
                <owl:onProperty rdf:resource="#is-part-of"/>
                <owl:allValuesFrom rdf:resource="#tree"/>
        </owl:Restriction>
    </rdfs:subClassOf>
</owl:Class>
```

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>
```

African Wildlife: Herbivores

```
<owl:Class rdf:ID="herbivore">
   <rdfs:comment>
     Herbivores are exactly those animals
     that eat only plants or parts of plants.
   </rdfs:comment>
   <rdfs:comment>
     Try it out! See book for code.
   <rdfs:comment>
</owl:Class>
```

African Wildlife: Giraffes

```
<owl:Class rdf:ID="giraffe">
    <rdfs:comment>Giraffes are herbivores, and they
    eat only leaves.</rdfs:comment>
    <rdfs:subClassOf rdf:type="#herbivore"/>
    <rdfs:subClassOf>
       <owl:Restriction>
             <owl:onProperty rdf:resource="#eats"/>
             <owl:allValuesFrom rdf:resource="#leaf"/>
       </owl:Restriction>
    </rdfs:subClassOf>
</owl:Class>
```

African Wildlife: Lions

```
<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>
```

African Wildlife: Tasty Plants

```
owl:Class rdf:ID="tasty-plant">
  <rdfs:comment>Plants eaten both by herbivores
  and carnivores </rdfs:comment>
  <rdfs:comment>
      Try it out! See book for code.
  <rdfs:comment>
</owl:Class>
```

Printer Ontology – Class Hierarchy

Printer Ontology – Products and Devices

```
<owl:Class rdf:ID="product">
    <rdfs:comment>Products form a class. </rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="padid">
    <rdfs:comment>Printing and digital imaging devices
    form a subclass of products.</rdfs:comment>
    <rdfs:label>Device</rdfs:label>
    <rdfs:subClassOf rdf:resource="#product"/>
</owl:Class>
```

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

```
<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. Future Extensions

OWL in OWL

- 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

Classes of Classes (Metaclasses)

- The class of all OWL classes is itself a subclass of the class of all RDF Schema classes:

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

Metaclasses – Thing and Nothing

- **Thing** is most general object class in OWL
- **Nothing** is most specific class: the empty object class
- The following relationships hold:

$$Thing = Nothing \cup \overline{Nothing}$$

$$Nothing = \overline{Thing} = \overline{Nothing \cup \overline{Nothing}} = \overline{Nothing} \cap \overline{\overline{Nothing}} = \emptyset$$

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

```
<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>
```

Union and Intersection of Classes

- Build a class from a list, assumed to be a list of other class expressions

```
<rdf:Property rdf:ID="unionOf">
        <rdfs:domain rdf:resource="#Class"/>
        <rdfs:range rdf:resource="&rdf;List"/>
</rdf:Property>
```

Restriction Classes

- Restrictions in OWL define the class of those objects that satisfy some attached conditions

```
<rdfs:Class rdf:ID="Restriction">
        <rdfs:label>Restriction</rdfs:label>
        <rdfs:subClassOf
    rdf:resource="#Class"/>
</rdfs:Class>
```

Restriction Properties

- 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

Restriction Properties

```
<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**

```
<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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Future Extensions of OWL

- Modules and Imports
- Defaults
- Closed World Assumption
- Unique Names Assumption
- Procedural Attachments
- Rules for Property Chaining

Modules and Imports

- 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

Defaults

- 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 currently an active area of research

OWL 1.1

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 modeling 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