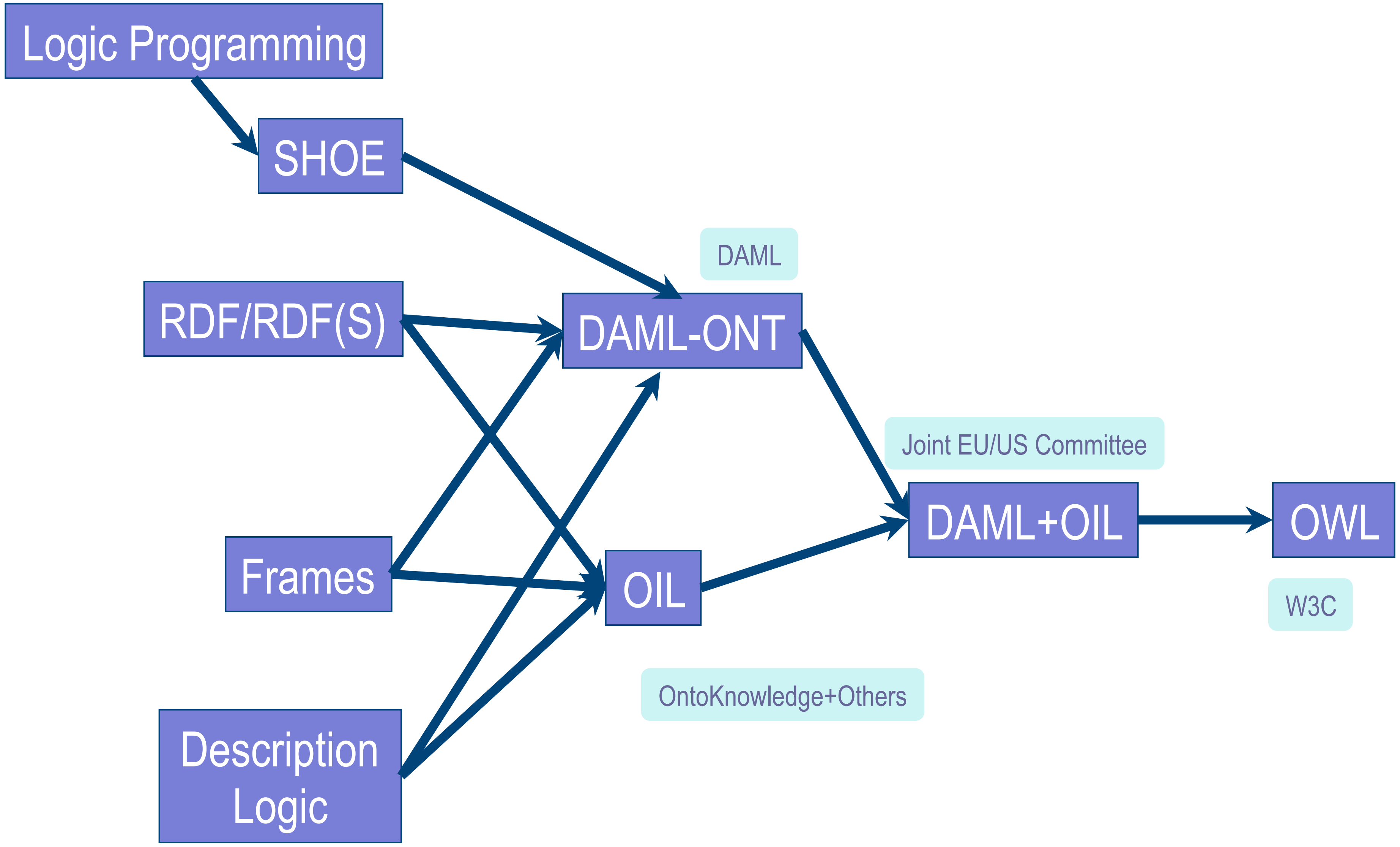
Chapter 4
OWL

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. OWL 2

The OWL Family Tree



A Brief History of OWL: SHOE

- Simple HTML Ontology Extensions
- Sean Luke, Lee Spector, and David Rager, 1996

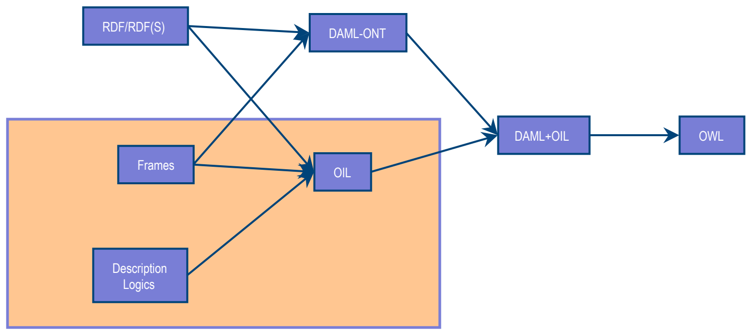
  SHOE allows World-Wide Web authors to annotate their pages with ontology-based knowledge about page contents. We present examples showing how the use of SHOE can support a new generation of knowledge-based search and knowledge discovery tools that operate on the World-Wide Web.
- Supported adding “semantic”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

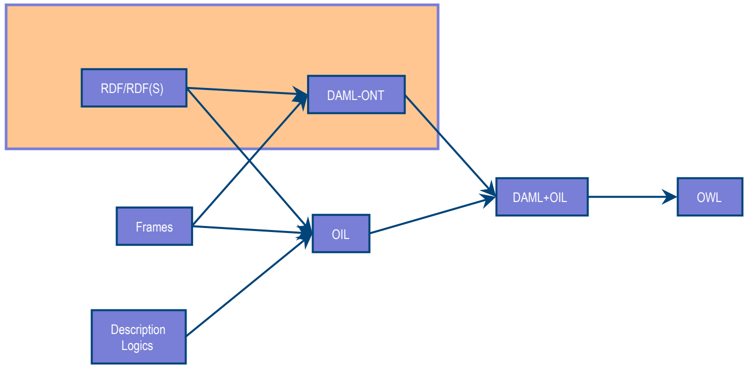
A Brief History of OWL: OIL

- Developed by group of (largely) European researchers (several from EU OntoKnowledge project)
- Based on frame-based KR languages
- Strong emphasis on formal rigour
- Semantics in terms of description dogics
- RDFS based syntax



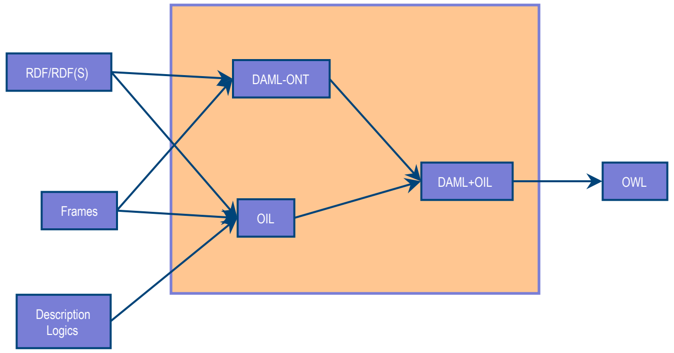
A Brief History of OWL: DAML-ONT

- 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



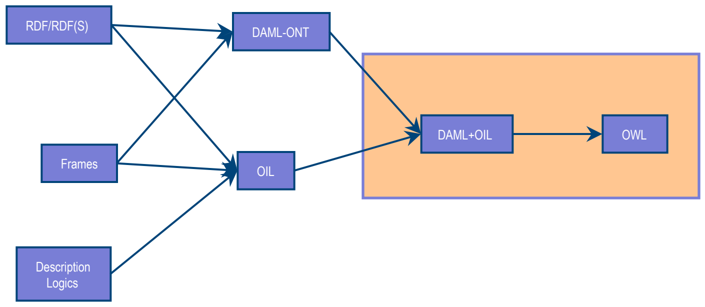
A Brief History of OWL: DAML+OIL

- Merging of DAML-ONT and OIL
- Basically a DL with an RDFS-based syntax
- Development 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 logic
  - Relationship with RDF
- Comprehensive test cases for tools/implementations
- Growing industrial take up.



OWL 2

- Is an **extension of OWL**
  - Addresses deficiencies identified by users and developers (at **OWLED workshop**)
- Is based on more expressive DL: **SROIQ**
  - OWL is based on **SHOIN**
- W3C **working group** chartered
  - http://www.w3.org/2007/OWL/wiki/OWL_Working_Group
  - Became a W3C recommendation October 2009
- **Supported** by popular OWL tools
  - Protégé, TopBraid, FaCT++, Pellet

Outline

Ontology and Data

- In philosophy, an ontology is a model of what exists in the world (kinds of things, properties, etc.)
- In information systems, it's roughly a schema for information or data
- In a KR language, it's typically a model of classes and relations/properties and axioms that go with them (e.g., subPropertyOf is transitive)
- Data comprise 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)

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’s always a tradeoff between expressive power and efficient reasoning support
- The richer the language is, the more inefficient the reasoning support becomes
- Reasoning can be undecidable or semi-decidable and even if decidable can be exponentially hard
- 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 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 the consistency of the ontology and the 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 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 1

- 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's undecidable
  - No complete (or efficient) reasoning support

Soundness and completeness

- A sound reasoner only makes conclusions that logically follow from the input, i.e., all of it’s conclusions are correct
  - We almost always require our reasoners to be sound
- A complete reasoner can make all conclusions that logically follow from the input
  - We can not guarantee complete reasoners for full FOL and many subsets
  - We can’t do it for OWL

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

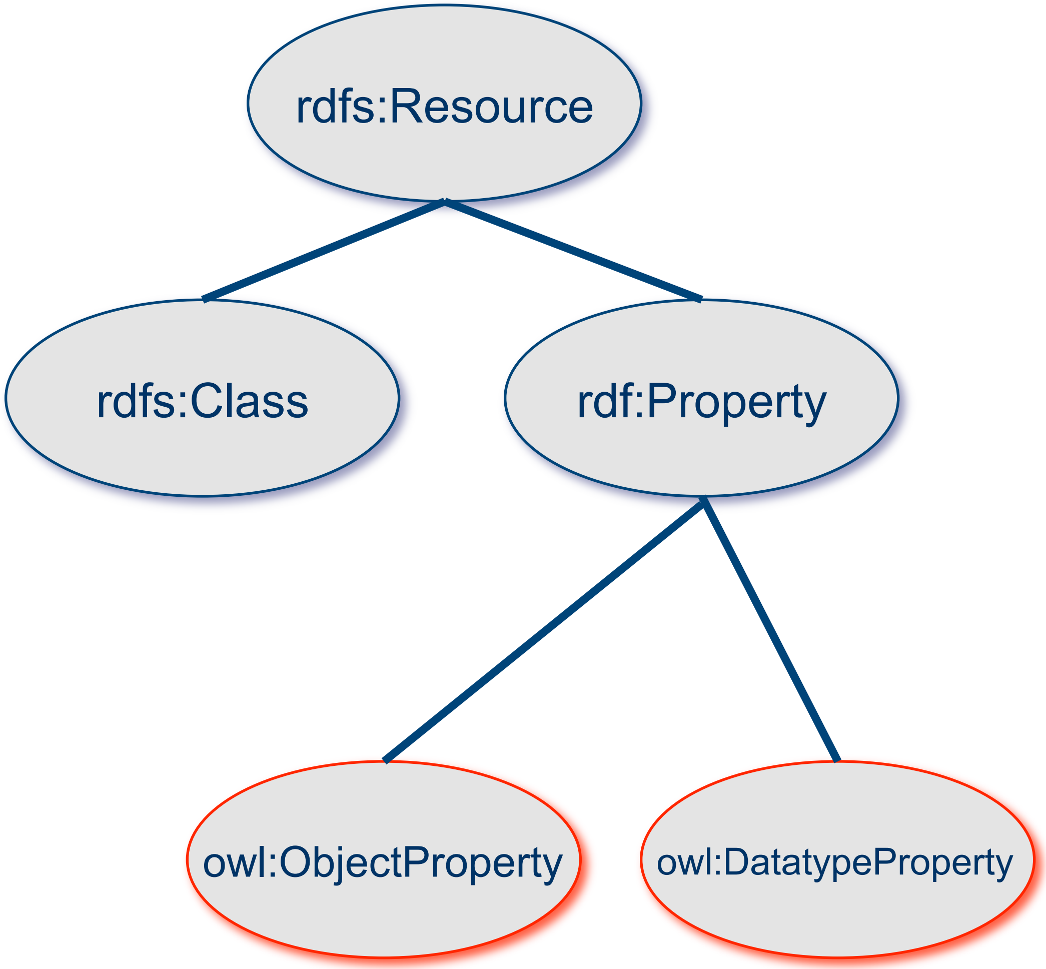
- An even further restriction limits OWL DL to a subset of the language constructors
  - E.g., OWL Lite excludes enumerated classes, disjointness statements, and arbitrary cardinality
- The advantage of this is a language that is easier to
  - grasp, for users
  - implement, for tool builders
- The disadvantage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

OWL Compatibility with RDF Schema

- 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



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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4. Examples
5. The OWL Namespace
6. Future Extensions

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
  - RDF serializations – Turtle, Ntriples, etc.
  - Several abstract syntaxes that are more compact and readable than XML
  - 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 (aka literals)
- Disjointness is defined using **owl:disjointWith**
  - Two disjoint classes are can share no instances

Separate Objects & 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:

      d'_1 Å … Å d'_n, where d 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 rdfs: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.
- These were made separate to make it easier to create sound and complete reaonsers

Datatype Properties

- OWL uses XML Schema data types, exploiting 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">
  <rdfs:domain rdf:resource="#course"/>
  <rdfs: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  owl:inverseOf ?Q. ?S ?P ?O} => {?O ?Q ?S}.
{?P owl:inverseOf ?Q. ?P  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>
```

Offspring of people are people

```
<!– The offspring of a Person is a Person -->
<rdf:Description rdf:about="foaf:Person">
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="bio:offspring"/>
       <owl:allValuesFrom rdf:resource="foaf:Person"/>
     </owl:Restriction>
   </rdfs:subClassOf>
</rdf:Description>
```

Literally: *Person is a sub-class of things all of whose offspring are necessarily of type Person*

{?X a foaf:Person. ?X bio:offspring ?O} => {?O a Person}

Offspring of people are people

```
<rdf:RDF
  xmlns:="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
  xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
  xmlns:owl="http://www.w3.org/2002/07/owl#"
  xmlns:foaf="http://xmlns.com/foaf/0.1/"
  xmlns:bio="http://example.com/bio/" >
<Description about="foaf:Person">
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty resource="bio:offspring" />
        <owl:allValuesFrom resource="foaf:Person"/>
    </owl:Restriction>
  </rdfs:subClassOf>
</Description>
```

And in turtle

```
n3> cwm --rdf restriction.xml --n3
...
@prefix : <http://www.w3.org/2002/07/owl#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .

    <foaf:Person> a :Class;
         rdfs:subClassOf
             [ a :Restriction;
               :allValuesFrom <foaf:Person>;
               :onProperty <bio:offspring> ] .
#ENDS
```

```
# a thing of type
# owl:restriction where all
# of its bio:offspring values
# are of type foaf:Person
```

What follows?

```
<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.
???
```

What follows?

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

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

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

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>
  <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>
```

A typical example

```
:male owl:equivalentClass
   owl:intersectionOf
   ( foaf:Person,
     [:onProperty :sex;
      :owl:hasValue “male”] ).
```

What follows?

:ed a :male?

???

:frank a foaf:Person; :sex “male”.

???

:gerry a foaf:Person; :sex “male”; :sex “female” .

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** & **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>
```

What does this say?

```
<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>
```

Definition of a parent

The parent class is equivalent to the class of things that have at least one child

All(x): Parent(x) ⇔ Exisits(y) 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

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>
</owl:Class>
```

Boolean Combinations

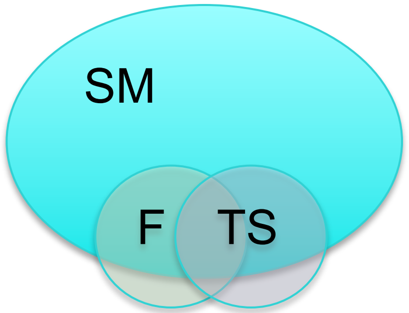
- *E.g., CS faculty is the intersection of faculty and things that belongTo the CS Department.*

```
<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** says 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
- 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**)

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**

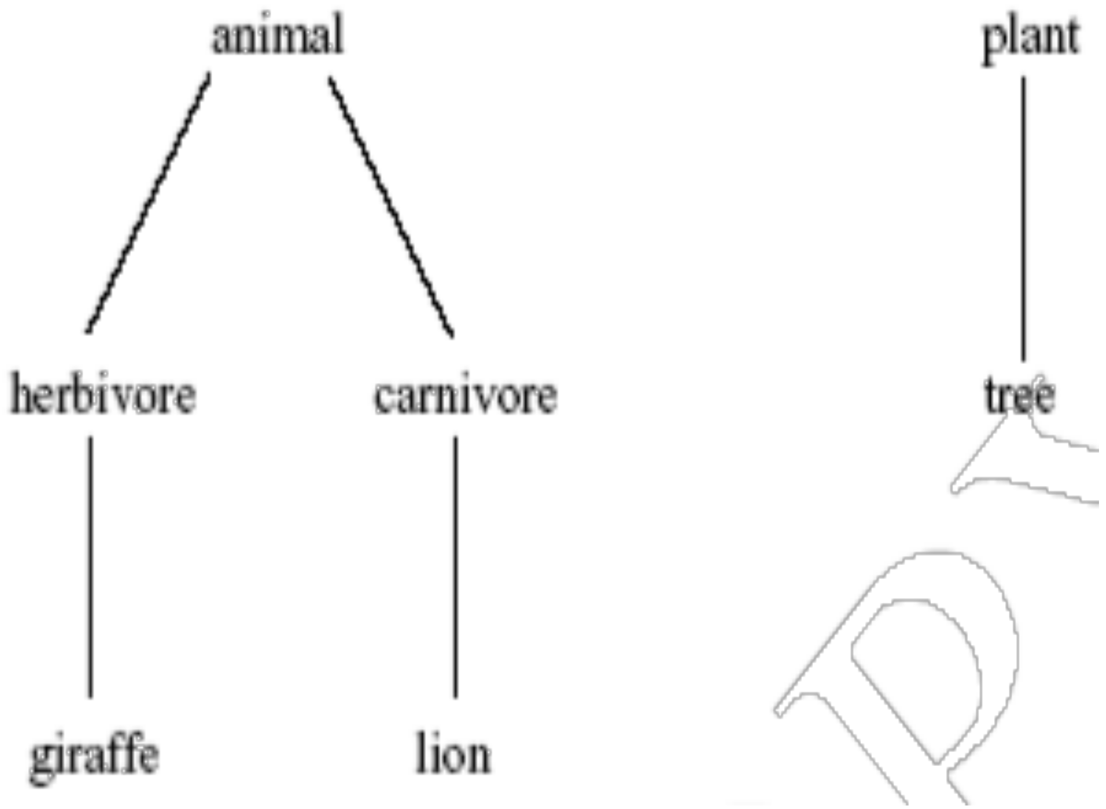
Restriction of Features in OWL Lite

- 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

Outline

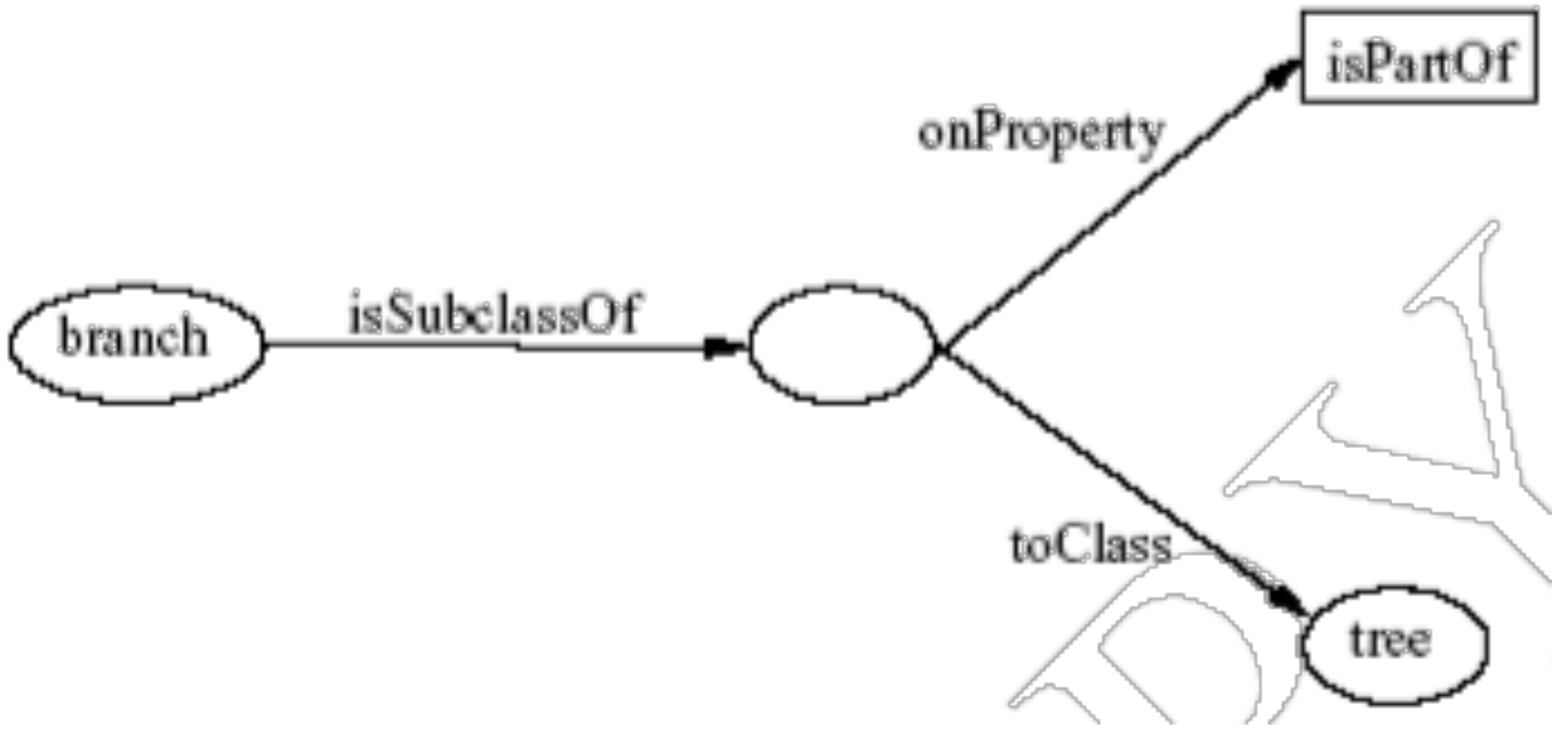
1. A bit of history
2. Basic Ideas of OWL
3. The OWL Language
4. **Examples**
5. The OWL Namespace
6. Future Extensions

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

How can we define Herbivores?

African Wildlife: Herbivores

Here is one approach

```
<owl:Class rdf:ID="herbivore">
    <rdfs:comment>
      Herbivores are exactly those animals that
        eat only plants or parts of plants.
    </rdfs:comment>
    ????????????????????
</owl:Class>
```

```
<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>
      </class>
    </owl:allValuesFrom>
   </owl:Restrcition>
 </owl:intersectionOf>
</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

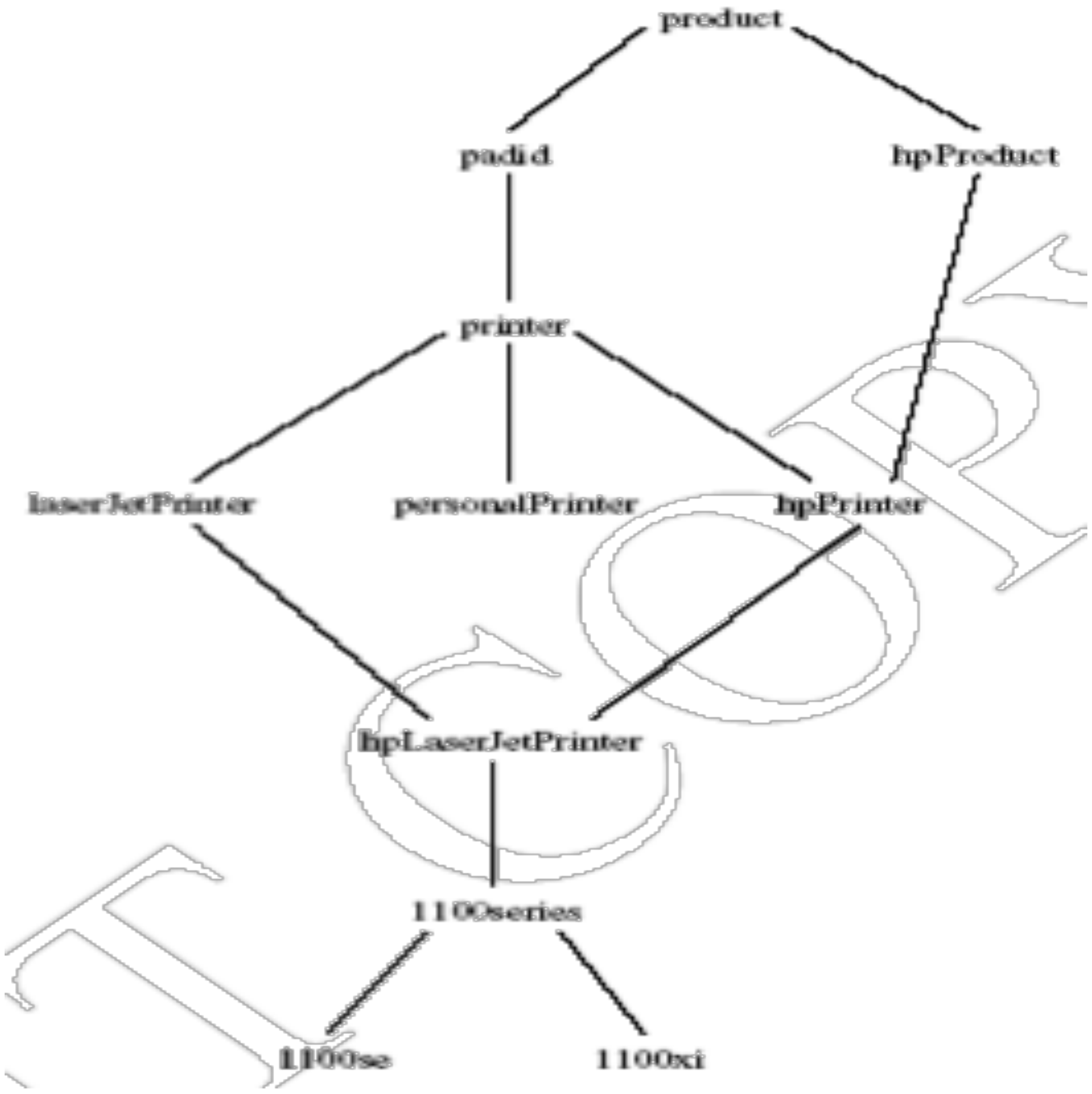
```
<owl:Class rdf:ID="lion">
   <rdfs:comment>Lions are animals that eat
   only herbivores.</rdfs:comment>
   <rdfs:subClassOf rdf:type="#carnivore"/>
   <rdfs:subClassOf>
      <owl:Restriction>
        <owl:onProperty rdf:resource="#eats"/>
        <owl:allValuesFrom rdf:resource="#herbivore"/>
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

```
<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>
   </rdfsSublassOf>
</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

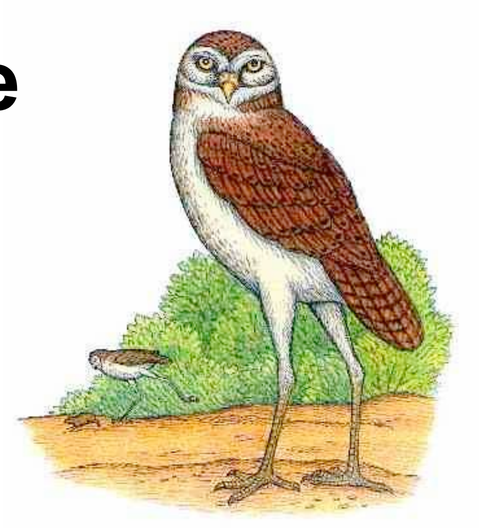
```
<owl:Class rdf:ID="1100se">
    <rdfs:comment>1100se printers belong to the 1100
    series and cost $450.</rdfs:comment>
    <rdfs:subClassOf rdf:resource="#1100series"/>
    <rdfs:subClassOf>
        <owl:Restriction>
                <owl:onProperty rdf:resource="#price"/>
                <owl:hasValue><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



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:

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

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

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>
```

Outline

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 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 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