1. A bit of history
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The OWL Family Tree

- Logic Programming
  - SHOE
  - RDF/RDF(S)
  - DAML-ONT
  - DAML
  - Joint EU/US Committee
  - OntoKnowledge+Others
- Description Logic
- Frames
- Logic Programming
- Description Logic
- Frames
- OWL
- W3C
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.
- Supported adding “semantic” tags defined in an ontology plus prolog-like rules to web pages.
<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 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 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
  - Became a W3C recommendation October 2009
- Supported by popular OWL tools
  - Protégé, TopBraid, FaCT++, Pellet
Outline

1. A bit of history
2. **Basic Ideas of OWL**
3. The OWL Language
4. Examples
5. The OWL Namespace
6. OWL 2
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)
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
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 (or efficient) reasoning support
A sound reasoner only makes conclusions that logically follow from the input, i.e., all of its 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 cannot guarantee complete reasoners for full FOL and many subsets
- We can’t do it for OWL
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.
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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6. Future Extensions
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 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**

```xml
<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:*
  
  \[ d_1 \land \ldots \land d_n, \]  
  
  where \( d \) is a (possibly negated) datatype
<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
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 reasoners.
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/XMLSchema#nonNegativeInteger"/>
  <rdfs:domain rdf:resource="foaf:Person"/>
</owl:DatatypeProperty>
```
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.


Equivalent Properties

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

- Two properties have the same property *extension*
- Axioms
  
  \iff \{?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
• 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}
<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>
</rdf:RDF>
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>;

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

#ENDS
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" .
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.

```xml
<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.

```xml
<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>
```
<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

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

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
<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>
We can combine classes using Boolean operations (union, intersection, complement).

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

```xml
<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>
            ...<owl:allValuesFrom>
          </owl:Restriction>
        </owl:allValuesFrom>
      </owl:allValuesFrom>
    </owl:Restriction>
  </rdfs:subClassOf>
</owl:Class>
```
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.

```xml
<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

```xml
<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, ...

```xml
<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

```xml
<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>
```
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:

```xml
<lecturer rdf:about="949318">
  <owl:differentFrom rdf:resource="949352"/>
</lecturer>
```
OWL provides a shorthand notation to assert the pairwise inequality of all individuals in a given list:

```xml
<owl:allDifferent>
  <owl:distinctMembers rdf:parseType="Collection">
    <lecturer rdf:about="949318"/>
    <lecturer rdf:about="949352"/>
    <lecturer rdf:about="949111"/>
  </owl:distinctMembers>
</owl:allDifferent>
```
XML Schema provides a mechanism to construct user-defined data types
  - E.g., the data type of \texttt{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 \texttt{string}, \texttt{integer}, \texttt{Boolean}, \texttt{time}, and \texttt{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
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3. The OWL Language
4. **Examples**
5. The OWL Namespace
6. Future Extensions
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>
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>
<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?
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>
        </owl:Class>
        <owl:allValuesFrom rdf:resource="#plant"/>
      </owl:Restriction>
    </owl:allValuesFrom>
  </owl:Restriction>
  <owl:allValuesFrom>
  </owl:allValuesFrom>
</owl:Restriction>
</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>
  <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>
          <owl:onProperty rdf:resource="#eaten_by"/>
          <owl:someValuesFrom> <owl:Class rdf:about="#carnivore"/>
          <owl:someValuefrom>
            </owl:Restriction>
        </owl:Restriction>
      </owl:someValuefrom>
    </owl:Restriction>
  </rdfs:subClassOf>
</owl:Class>
Printer Ontology – Class Hierarchy
<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>
<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>
Printers are printing and digital imaging devices.

Printers for personal use form a subclass of printers.
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

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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>
```
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:

\[
\begin{align*}
\text{Thing} & = \text{Nothing} \cup \text{Nothing} \\
\text{Nothing} & = \text{Thing} = \text{Nothing} \cup \text{Nothing} = \text{Nothing} \cap \text{Nothing} = \emptyset
\end{align*}
\]
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

```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.

```
<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

```xml
<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>
```
<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.

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