Semantic Web in Depth:
Web Ontology Language (OWL)

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Introducing OWL

- For many, RDF Schema is a sufficiently expressive ontology language
- However, there are use cases which require a more expressive formalism:
  - Instance classification
  - Consistency checking
  - Subsumption reasoning
OWL Feature Summary

- Necessary and sufficient conditions for class membership
- Property restrictions
  - Local range, cardinality, value constraints
- Equivalence and identity relations
- Property characteristics
  - Transitive, symmetric, functional
- Complex classes
  - Set operators, enumerated classes, disjoint classes
Two versions of OWL:

- OWL 1.0 (became Recommendation on 10 Feb 2004)
- OWL 2 (became Recommendation on 29 Oct 2009)

OWL 2 is more expressive than OWL 1.0, and takes advantage of developments in DL reasoning techniques in the intervening time.

We will initially concentrate on OWL 1.0
Different subsets of OWL features give rise to the following sublanguages (colloquially known as species):

- OWL Lite
- OWL DL
- OWL Full

“There is a tradeoff between the expressiveness of a representation language and the difficulty of reasoning over the representations built using that language.”

OWL 1.0 Species

- RDF(S)
- OWL Lite
- OWL DL
- OWL Full

Increasing expressivity

Increasing complexity
OWL Lite

- Description Logic-based
  - $SHIF(D)$
- Less complex reasoning at the expense of less expressive language
  - No enumerated classes, set operators, or disjoint classes
  - Restricted cardinality restrictions
    (values of 0 or 1 – required, permitted and excluded)
  - No value restrictions
  - equivalentClass/subClassOf cannot be applied to class expressions
OWL DL

- Description Logic-based
  - $SHOIN(D)$
  - Complete and decidable
  - Higher worst-case complexity than OWL Lite
- Supports all OWL constructs, with some restrictions
  - Properties that take datatype values cannot be marked as inverse functional
  - Classes, properties, individuals and datatype values are disjoint
OWL Full

• No restrictions on use of language constructs
  • All OWL DL and RDFS constructs

• Potentially undecidable
OWL 1.0 Features and Syntax
Ontology header

• Ontology header for metadata

<owl:Ontology rdf:about="">
  <owl:versionInfo>1.4</owl:versionInfo>
  <rdfs:comment>An example ontology</rdfs:comment>
  <owl:imports
    rdf:resource="http://www.example.org/base"/>
</owl:Ontology>
Versioning support

• Version properties used in the ontology header
  • owl:versionInfo
    • Version number, etc
  • owl:priorVersion
    • Indicates that an ontology is a previous version of this
  • owl:backwardCompatibleWith
    • Indicates that the specified ontology is a previous version of this one, and that this is compatible with it
  • owl:incompatibleWith
    • Indicates that the specified ontology is a previous version of this one, but that this is incompatible with it
Versioning support

- Classes and properties may be marked as deprecated
  - owl:DeprecatedClass
  - owl:DeprecatedProperty
OWL class types

- **owl:Class**
  - Distinct from rdfs:Class – needed for OWL Lite/DL

- **owl:Thing (⊤)**
  - The class that includes everything

- **owl:Nothing (⊥)**
  - The empty class
OWL property types

- **owl:ObjectProperty**
  - The class of resource-valued properties

- **owl:DatatypeProperty**
  - The class of literal-valued properties

- **owl:AnnotationProperty**
  - Used to type properties which annotate classes and properties (needed for OWL Lite/DL)
Recall that the semantics of a description logic is specified by interpretation functions which map:

- Instances to members of the domain of discourse
- Classes to subsets of the domain of discourse
- Properties to sets of pairs drawn from the domain of discourse

Reflexive definitions of RDF Schema means that some resources are treated as both classes and instances, or instances and properties.

Ambiguous semantics for these resources:
- Can’t tell from context whether they’re instances or classes
- Can’t select the appropriate interpretation function

The introduction of owl:Class, owl:ObjectProperty and owl:DatatypeProperty eliminates this ambiguity.
OWL’s Dirty Secret Uncovered

- OWL Full
- OWL DL
- OWL Lite
- RDF(S)
- RDF(S)’
OWL restrictions

• Class expression formed by constraints on properties
  • Local cardinality constraints
    \( \leq n R, \geq n R, = n R \)
  • Local range constraints
    \( \exists R.C, \forall R.C \)
  • Local value constraints
    \( \exists R.\{x\} \)
  • Key concept in OWL
<owl:Restriction>
  <owl:onProperty rdf:resource="property"/>
  constraint expression
</owl:Restriction>
Local cardinality constraints

- Defines a class based on the number of values taken by a property
- `owl:minCardinality (≥ n R)`
  - “property R has at least n values”
- `owl:maxCardinality (≤ n R)`
  - “property R has at most n values”
- `owl:cardinality (= n R)`
  - “property R has exactly n values”

- OWL Lite has restricted cardinalities
Local cardinality constraints

• Single malt whiskies are whiskies which are distilled by one and only one thing

<owl:Class rdf:about="#SingleMaltWhisky">
  <owl:equivalentClass>
    <owl:Class>
      <owl:intersectionOf rdf:parseType="Collection">
        <owl:Class rdf:about="#Whisky"/>
        <owl:Restriction>
          <owl:onProperty rdf:resource="#distilledBy"/>
          <owl:cardinality>1</owl:cardinality>
        </owl:Restriction>
      </owl:intersectionOf>
    </owl:Class>
  </owl:equivalentClass>
</owl:Class>
Local range constraints

• Defines a class based on the type of property values
• Distinct from global range constraint (rdfs:range) in RDF Schema
• owl:someValuesFrom (∃R.C)
  • “there exists a value for property R of type C”
• owl:allValuesFrom (∀R.C)
  • “property R has only values of type C”

• Can only be used with named classes or datatypes in OWL Lite
Local range constraints

- Carnivores are things which eat some things which are animals (∃eats.Animal)

```xml
<owl:Class rdf:about="#Carnivore">
  <owl:equivalentClass>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#eats"/>
      <owl:someValuesFrom rdf:resource="#Animal"/>
    </owl:Restriction>
  </owl:equivalentClass>
</owl:Class>
```
Vegetarians are things which eat only things which are plants (∀eats.Plant)

```xml
<owl:Class rdf:about="#Vegetarian">
  <owl:equivalentClass>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#eats"/>
      <owl:allValuesFrom rdf:resource="#Plant"/>
    </owl:Restriction>
  </owl:equivalentClass>
</owl:Class>
```
Local value constraints

- Defines a class based on the existence of a particular property value
- `owl:hasValue (∃R.{x})`
  - “property R has a value which is X”
- Cannot be used in OWL Lite
Green things are things which are coloured green
(∃ R. \{ Green \})

```xml
<owl:Class rdf:about="#GreenThing">
  <owl:equivalentClass>
    <owl:Restriction>
      <owl:onProperty rdf:resource="#hasColour" />
      <owl:hasValue rdf:resource="#Green" />
    </owl:Restriction>
  </owl:equivalentClass>
</owl:Class>
```
Set constructors

- `owl:intersectionOf (C \cap D)`
- `owl:unionOf (C \cup D)`
- `owl:complementOf (\neg C)`

Restrictions on use with OWL Lite

- `owl:unionOf` and `owl:complementOf` cannot be used
- `owl:intersectionOf` can be used with named classes (not bNodes) and OWL restrictions only
Set constructors example

<owl:Class rdf:about="GreenApple">
  <owl:equivalentClass>
    <owl:Class>
      <owl:intersectionOf rdf:parseType="Collection">
        <owl:Class rdf:about="Apple">
          <owl:Restriction>
            <owl:onProperty rdf:resource="hasColor"/>
            <owl:hasValue rdf:resource="Green"/>
          </owl:Restriction>
        </owl:Class>
      </owl:intersectionOf>
    </owl:Class>
  </owl:equivalentClass>
</owl:Class>
Equivalence and identity relations

- Useful for ontology mapping
  - owl:sameAs
  - owl:equivalentClass (C≡D)
  - owl:equivalentProperty (R≡S)

```xml
<owl:Thing rdf:about="#MorningStar">
  <owl:sameAs rdf:resource="#EveningStar"/>
</owl:Thing>
```
Non-equivalence relations

- owl:differentFrom
  - Can be used to specify a limited unique name assumption
    
    ```
    <rdf:Description rdf:about="#HarryCorbett">
      <owl:differentFrom rdf:resource="#HarryHCorbett"/>
    </rdf:Description>
    ```

- OWL (and DLs in general) make the Open World Assumption
  - Knowledge of world is incomplete
  - If something cannot be proven true, then it isn’t assumed to be false
Non-equivalence relations

- owl:AllDifferent and owl:distinctMembers
  - Used to specify a group of mutually distinct individuals

```
<owl:AllDifferent>
    <owl:distinctMembers rdf:parseType="Collection">
        <rdf:Description rdf:about="#John"/>
        <rdf:Description rdf:about="#Paul"/>
        <rdf:Description rdf:about="#George"/>
        <rdf:Description rdf:about="#Ringo"/>
    </owl:distinctMembers>
</owl:AllDifferent>
```
Class Definitions

• Necessary Conditions (\(\subseteq\))
  • Primitive / partial classes
  • “If we know that something is a X, then it must fulfill the conditions...”
  • Defined using rdfs:subClassOf

• Necessary and Sufficient Conditions (\(\equiv\))
  • Defined / complete classes
  • “If something fulfills the conditions..., then it is an X.”
  • Defined using owl:equivalentClass
Property types - Inverse

- Defines a property as the inverse of another property
  \( R \equiv S' \)

\[
\text{<owl:Property rdf:about="#hasAuthor">}
\text{  <owl:inverseOf rdf:resource="#wrote"/>}
\text{</owl:Property>}
\]
Property types - Symmetric

- Symmetric properties satisfy the axiom $P(x,y)$ iff $P(y,x)$
Property types – Transitive

- Transitive properties satisfy the axiom
  \( P(x,y) \) and \( P(y,z) \) implies \( P(x,z) \)

\[
<\text{owl:TransitiveProperty} \; \text{rdf:about}="\#hasAncestor"/>\]
Property types – Functional

• Functional properties satisfy the axiom $P(x,y)$ and $P(x,z)$ implies $y=z$

  <$owl:FunctionalProperty rdf:about="#hasNINumber"/>

(everyone has only one NI number)
Property types – Inverse Functional

- Inverse functional properties satisfy the axiom P(y,x) and P(z,x) implies y=z

\[
\langle \text{owl:InverseFunctionalProperty} \text{ rdf:about=\"#hasNINumber\"}/\rangle
\]

/people with the same NI number are the same person/

- Cannot be used with owl:DatatypeProperty in OWL Lite/DL
Disjoint classes

- owl:disjointWith
  - members of one class cannot also be members of some specified other class

```xml
<owl:Class rdf:about="#MaleHuman">
  <rdfs:subClassOf rdf:resource="#Human"/>
  <owl:disjointWith rdf:resource="#FemaleHuman"/>
</owl:Class>
```

- Cannot be used in OWL Lite
Enumerated classes

- Defines a class as a direct enumeration of its members
  - owl:one of \( C = \{a, b, c\} \)
- Cannot be extended (closed set)

- Cannot be used in OWL Lite
<owl:Class rdf:about="#Continents">
  <owl:oneOf rdf:parseType="Collection">
    <owl:Thing rdf:about="#Africa"/>
    <owl:Thing rdf:about="#Antarctica"/>
    <owl:Thing rdf:about="#Oceania"/>
    <owl:Thing rdf:about="#Europe"/>
    <owl:Thing rdf:about="#North-America"/>
    <owl:Thing rdf:about="#South-America"/>
    <owl:Thing rdf:about="#Asia"/>
  </owl:oneOf>
</owl:Class>
Ontology modularisation

- owl:imports mechanism for including other ontologies
- Also possible to use terms from other ontologies without explicitly importing them
- Importing requires certain entailments, whereas simple use does not require (but also does not prevent) those entailments
Ontology modularisation example

- Ontology 1 (ont1) contains:
  BBB rdfs:subClassOf AAA
- Ontology-2 (ont2) contains:
  ont2 imports ont1
  CCC rdfs:subClassOf BBB
- Ontology-2 must entail
  CCC rdfs:subClassOf AAA
Ontology modularisation example

• Ontology 1 (ont1) contains:
  BBB rdfs:subClassOf AAA
• Ontology-3 (ont3) contains:
  CCC rdfs:subClassOf ont1:BBB

• Ontology-3 does **not necessarily** entail
  CCC rdfs:subClassOf ont1:AAA
OWL status

- WebOnt working group formed Nov 2001
- OWL Recommendations published in Feb 2004
OWL references

- Web Ontology Working Group homepage
  - http://www.w3.org/2001/sw/WebOnt/
From OWL 1 to OWL 2

• OWL 1 design based on contemporary understanding of techniques for decidable, sound and complete reasoning in description logics

• Our understanding has improved since 2004
  • Some things that looked intractable have been shown to be possible

• Changes between 1 and 2 fall into the following categories:
  • Syntactic sugar (making it easier to say things we could already say)
  • Constructs for increased expressivity
  • Datatype support
  • Metamodelling
  • Annotation
Syntactic Sugar: Disjoint Union

• Allows us to define a class as the union of a number of other classes, all of which are pairwise disjoint

\[ C \equiv C_1 \sqcup C_2 \sqcup \ldots \sqcup C_n \]

\[ C_1 \sqcap C_2 \equiv \bot \]

• We’ll look at this modelling pattern more in later lectures
Syntactic Sugar: Disjoint Classes

- OWL 1 lets us state that two classes are disjoint

- OWL 2 lets us state that a set of classes are pairwise disjoint
Syntactic Sugar: Negative Property Assertions

• OWL 1 lets us assert property values for an individual

• OWL 2 lets us assert that an individual does not have a particular property value

<owl:NegativePropertyAssertion>
  <owl:sourceIndividual rdf:resource="john"/>
  <owl:assertionProperty rdf:resource="hasChild"/>
  <owl:targetIndividual rdf:resource="susan"/>
</owl:NegativePropertyAssertion>
New Constructs: Self Restriction

- Define a class of individuals which are related to themselves by a given property

```xml
<owl:Restriction>
  <owl:onProperty rdf:resource="..."/>
  <owl:hasSelf rdf:datatype="&xsd:boolean">true</owl:hasSelf>
</owl:Restriction>
```
New Constructs: Qualified Cardinality Restrictions

• OWL 1 lets us either specify the local range of a property, or the number of values taken by the property
• OWL 2 lets us specify both together:

$$= 4 \ hasPart.Wheel$$

```xml
<owl:Restriction>
  <owl:onProperty rdf:resource="hasPart"/>
  <owl:onClass rdf:resource="Wheel"/>
  <owl:cardinality rdf:datatype="&xsd;integer">4</owl:cardinality>
</owl:Restriction>
```

• Similar construct for datatype properties
New Constructs: Reflexive Properties

• Allows us to assert that a property is globally reflexive (relates every object to itself)

<owl:ReflexiveProperty rdf:about="sameAgeAs"/>
New Constructs:
Irreflexive Properties

- Allows us to assert that a property relates no object to itself

<owl:IrreflexiveProperty rdf:about="strictlyTallerThan"/>
New Constructs: Asymmetric Properties

- Allows us to assert that a property is asymmetric:
  - If $p(x,y)$, then not $p(y,x)$

<owl:AsymmetricProperty rdf:about="strictlyTallerThan"/>
New Constructs: Disjoint Properties

- Allows us to state that two individuals cannot be related to each other by two different properties that have been declared disjoint

```xml
<owl:ObjectProperty rdf:about="connectedTo">
    <owl:propertyDisjointWith rdf:resource="contiguousWith"/>
</owl:ObjectProperty>
```
New Constructs: Property Chain Inclusion

• OWL 1 does not let us define a property as a composition of other properties
  • Example: hasUncle ≡ hasParent o hasBrother

• OWL 2 lets us define such property compositions

```xml
<owl:ObjectProperty rdf:about="hasUncle">
    <owl:propertyChainAxiom rdf:parseType="Collection">
        <owl:ObjectProperty rdf:about="hasParent"/>
        <owl:ObjectProperty rdf:about="hasBrother"/>
    </owl:propertyChainAxiom>
</owl:ObjectProperty>
```
New Constructs: Keys

• OWL 1 lets us define a property to be functional, so that individuals can be uniquely identified by values of that property
• OWL 2 lets us define uniquely identifying keys that comprise several properties

<owl:Class rdf:about="Person">
  <owl:hasKey rdf:parseType="Collection">
    <owl:DatatypeProperty rdf:about="hasSSN"/>
    <owl:DatatypeProperty rdf:about="birthDate"/>
  </owl:hasKey>
</owl:Class>
Datatype Restrictions

• Allows us to define subsets of datatypes that constrain the range of values allowed by a datatype
• For example, the datatype of integers greater than or equal to 5:

```xml
<owl:Datatype>
    <owl:onDatatype rdf:resource="&xsd;integer"/>
    <owl:withRestrictions rdf:parseType="Collection">
        <xsd:minInclusive>
            <xsd:integer rdf:datatype="&xsd;integer">5</xsd:integer>
        </xsd:minInclusive>
    </owl:withRestrictions>
</owl:Datatype>
```
Metamodelling: Punning

- OWL 1 required the names used to identify classes, properties, individuals and datatypes to be disjoint

- OWL 2 relaxes this
  - The same name (URI) can be used for both a class and an individual

- However:
  - A name cannot be used for both a class and a datatype
  - A name cannot be used for more than one type of property (DataProperty vs ObjectProperty)
• OWL 1 has three dialects: OWL Lite, OWL DL and OWL Full

• OWL 2 introduces three profiles with useful computational properties (reasoning, conjunctive queries):
  • OWL 2 EL (PTIME-complete, PSPACE-complete)
  • OWL 2 QL (NLOGSPACE-complete, NP-complete)
  • OWL 2 RL (PTIME-complete, NP-complete)

• OWL 1 DL (NEXPTIME-complete, decidability open)
Manchester DL Syntax
A Plethora of Syntaxes

• The DL syntax we’ve used so far is a ‘traditional’ syntax for logical expressions

• Not well understood by non-logicians

• The Manchester DL syntax was introduced as a more user-friendly syntax for use in tools
  • Used in Protégé 4 – the subject of our next lecture
### Manchester Syntax Summary

<table>
<thead>
<tr>
<th>Traditional DL Syntax</th>
<th>Manchester Syntax</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C \sqcap D$</td>
<td>C and D</td>
</tr>
<tr>
<td>$C \sqcup D$</td>
<td>C or D</td>
</tr>
<tr>
<td>$\neg C$</td>
<td>not C</td>
</tr>
<tr>
<td>$\exists R.C$</td>
<td>R some C</td>
</tr>
<tr>
<td>$\forall R.C$</td>
<td>R only C</td>
</tr>
<tr>
<td>$\geq n R$</td>
<td>R min n</td>
</tr>
<tr>
<td>$\leq n R$</td>
<td>R max n</td>
</tr>
<tr>
<td>$= n R$</td>
<td>R exactly n</td>
</tr>
<tr>
<td>$\exists R.{x}$</td>
<td>R value x</td>
</tr>
<tr>
<td>$\geq n R.C$</td>
<td>R min n C</td>
</tr>
<tr>
<td>Reflexive property</td>
<td>R Self</td>
</tr>
<tr>
<td>Datatype restrictions</td>
<td>int[(\geq 2, \leq 15)]</td>
</tr>
</tbody>
</table>
The Protégé Ontology Editor
Protégé

- Leading ontology editor
- Early implementer of OWL (but was around before OWL)
- Thriving user community
  - Annual user conference
- Free and open source
  - http://protege.stanford.edu/
  - Many add-ons for visualisation, etc
Protégé integrates reasoning into the ontology design process
  • Checks your ontology for consistency, subsumption, etc
  • Uses DIG interface to communicate with the reasoner
• Pellet
  • http://pellet.owldl.com/
• FaCT++
  • http://owl.man.ac.uk/factplusplus/
ESSENTIAL READING!

- (available from COMP6028 website)
Example ontology: OWL Pizzas

- Build an ontology for describing pizzas and their ingredients
- Must be able to determine whether pizzas are vegetarian, spicy, etc