OWL Reasoning

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Requirements for an Ontology Language

Ontology Languages allow users to write explicit, formal conceptualizations of domain models

- Extend existing Web Standards and build upon their syntax
  - Necessary conditions for machine processing information
  - XML, RDF, RDFS
- Easy to understand and use
  - Based on known Knowledge Representation Languages
- Sufficient Expressive Power
- Formal semantics
  - describe the meaning of knowledge *precisely* without being open to different interpretations
  - Essential for automated reasoning support

Limitations of RDF Schema

- Modeling primitives of RDF and RDFS concern the organization of *vocabularies* in *typed hierarchies*
  - *subclass* and *subproperty* hierarchies
  - *Global domain* and *range* definitions for *properties*
- Missing:
  - Disjointness of classes
  - Boolean combinations of class expressions
  - Cardinality restrictions
  - Special "characteristics" of properties
    - Transitive Properties
    - Uniqueness of property values …

A short history of Ontology Languages

- Web Ontology Working Group of W3C (2001) identified test cases that required more expressiveness than RDF/RDFS.
- Lead to a joint Initiative that produced DAML+OIL
  - *http://www.daml.org/2001/03/daml+oil-index.html*
  - Starting point for the **W3C Web Ontology Language (OWL)**
- OWL is an ontology language designed for the Semantic Web
  - Semantic Web Knowledge Representation Language for Web Resources (URIs) based on Description Logics (DLs)
  - Provides a rich collection of operators for forming concept descriptions
  - Promotes interoperation and sharing between applications
  - Designed to be compatible with existing web standards
    - Using Web-enabled syntaxes based on XML or RDF

W3C Web Ontology Language (OWL)

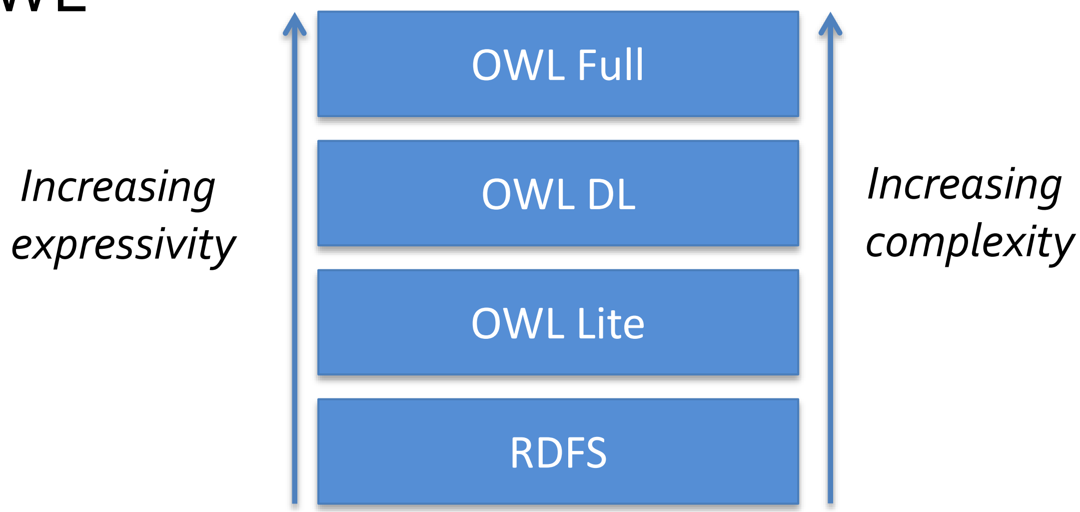
- Two versions of OWL:
  - OWL 1.0 W3C Recommendation for the Semantic Web (2004)
  - OWL2 Revised Recommendation (2009)
- OWL2 is more expressive than OWL1
  - Takes advantage of developments in DL reasoning techniques

Compatibility of OWL with RDFS

- Ideally OWL would be *an extension* of RDF Schema
  - OWL could use the RDF meaning of *classes* (rdfs:Class) and *properties* (rdf:Property) and add language primitives to support richer expressiveness
  - Be consistent with the layered architecture of the Semantic Web
  - Extension would work against obtaining expressive power and efficient reasoning leading to uncontrollable computational properties if logic is extended with expressive primitives
- Full Set of Requirements: Unobtainable
  - Definition of three different sublanguages of OWL, each geared toward fulfilling different aspects of the set of requirements

OWL Languages

- Three sublanguages of OWL
  - OWL Full
  - OWL DL
  - OWL Lite
- Syntactic Layering
- Semantic Layering
  - OWL DL semantics exactly the OWL Full Semantics (within the DL fragment)
  - OWL Lite semantics exactly the OWL DL semantics (within the Lite fragment)



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

Brachman and Levesque (1984)

OWL1: OWL Full

- Uses all OWL Language Primitives
- Allows the combination of primitives with RDF and RDFS in arbitrary ways
  - Includes the possibility of changing the meaning of predefined primitives
    - E.g., impose a cardinality constraint on the class of all classes hence limiting the number of classes one can describe in an ontology
    - Handle classes as instances (meta-modeling)
- Advantage: fully upward compatible with RDF both syntactically and semantically
  - Any legal RDF set of statements is also a legal OWL Full set of statements
- Disadvantage: Undecidable Language, no efficient reasoning support

OWL1: OWL DL

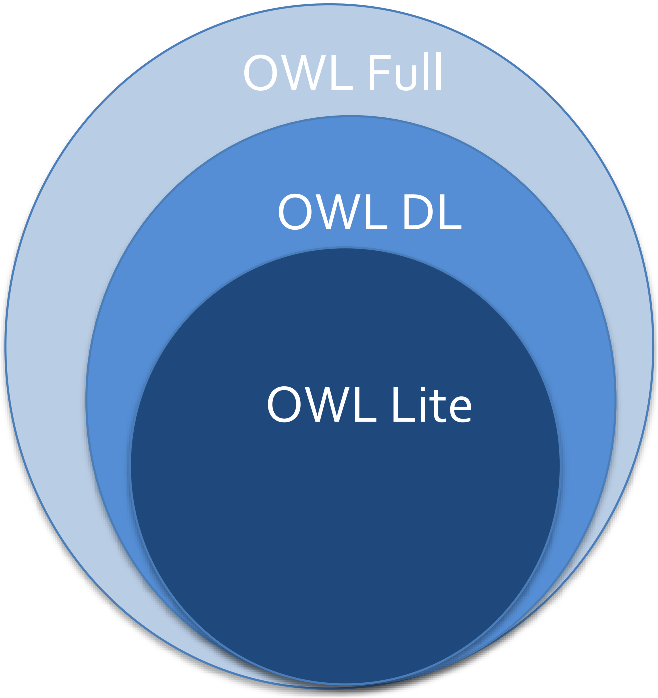
- Sublanguage of OWL Full
- Restricts how the constructors of OWL and RDF can be used
  - Cannot modify the semantics of predefined constructs
  - Classes cannot be used as instances
- Defined by an abstract syntax and mapping to RDF
- Direct mapping to DL/First Order Logic
- Advantages:
  - Well defined semantics
  - Well understood formal properties (complexity, decidability)
  - Efficient reasoning support
  - Highly Optimized Implemented Systems
- Disadvantage: no (direct) compatibility with RDF
  - Any legal RDF set of statements must be extended and or restricted in order to be a legal OWL DL dataset but every legal OWL DL set of statements is a legal set of RDF statements

OWL1: OWL Lite

- Sublanguage of OWL DL
  - No ability to support explicit negation or union
  - Excludes disjointness statements
  - Excludes enumerated classes as property range
  - Supports Cardinality constraints (zero or one)
    - A property of an instance can have zero or one values
- Direct mapping to DL/FOL
- Reasoning via standard RDF engines
  - Pellet, FaCT, RACER, OWLIM
- Advantage: Easiness of implementation, efficient reasoning
- Disadvantage: Limited Expressivity

OWL1: Which language for what?

- OWL Lite
  - Classification Hierarchy
  - Simple Constraints
- OWL DL
  - Maximal Expressiveness
  - Tractability is maintained
  - Standard Formalization
- OWL Full
  - Very high expressiveness
  - Tractability is lost
  - Non standard formalization
  - Syntactic Freedom of RDF



Syntactic and Semantic relationships between the OWL sub-languages

OWL1 : Syntax

- OWL in RDF
  - RDF/XML Syntax
- XML Presentation Syntax
  - Based on an XML Schema Definition
- Various syntaxes easier to be consumed by a human reader

OWL 1.0 Features and Syntax

- **Ontology header for metadata**

```
<owl:Ontology rdf:about="">
  <owl:versionOf>1.4</owl:versionOf>
  <rdfs:comment>An ontology about music</rdfs:comment>
  <owl:imports rdf:resource="http://dbpedia.org/">
</owl:Ontology>
```

- **Versioning Support**
  - owl:versionInfo (version information)
  - owl:priorVersion (prior version)
  - owl:backwardsCompatibleWith
    - Specified ontology is a prior version of current one and is compatible with it
  - owl:incompatibleWith
    - Specified ontology is a prior version of current one and is not compatible with it
  - Classes and properties can be declared as deprecated in the current ontology version
    - owl:DeprecatedClass
    - owl:DeprecatedProperty

OWL Classes & Properties

- ***Classes***
  - owl:Class
    - Distinct from rdfs:Class
    - Needed for OWL Lite/OWL DL
  - owl:Thing
    - Everything is a member of class owl:Thing
  - owl:Nothing
    - Represents the empty class
- ***Properties***
  - owl:topObjectProperty
    - A property that links every individual to every individual
  - owl:ObjectProperty
    - The class of properties whose value is a resource
  - owl:DataTypeProperty
    - The class of properties whose value is an atomic value

OWL Classes

- A class defines a group of individuals which share some properties
- A class is associated with a set of instances, called class extension
  - The individuals in the class extension are called the instances of the class
- A class has an intentional meaning (the underlying concept) which is related but not equal to its extension
  - Two classes may have the same class extension, but still be different classes.
- Class Descriptions
  1. a class identifier (a URI reference)
  2. an exhaustive enumeration of individuals that form the class extension
  3. a property restriction
  4. the intersection/union/complement of two or more class descriptions

1. Class Description: URI Reference

- Class *http://dbpedia.org#Artist* is the set of artists.
- Individual *http://dbpedia.org#TomWaits* is a *member (or instance)* of class *http://dbpedia.org#Artist*

Class Definition in RDF/XML

```
<owl:Class rdf:about="http://dbpedia.org#Artist">
        <rdfs:label rdf:datatype="&xsd;string” xml:lang=“en”>Artist</rdfs:label>
        <rdfs:label rdf:datatype="&xsd;string” xml:lang=“fr”>Artiste</rdfs:label>
</owl:Class>
```

Individual Definition in RDF/XML

```
<owl:NamedIndividual rdf:about="http://dbpedia.org#TomWaits">
        <rdf:type rdf:resource="http://dbpedia.org#Artist"/>
</owl:NamedIndividual>
```

OWL Classes

- Classes are organized in specialization hierarchies using built-in property rdfs:subClassOf
  - Class *http://dbpedia.org/ontology/Artist* is a subClassOf Class Person
- Built-in class *http://www.w3.org/2002/07/owl#Thing*
  - is the class of all individuals
  - is the superclass of all OWL classes
- Built-in class *http://www.w3.org/2002/07/owl#Nothing*
  - has no instances
  - is the subclass of all OWL classes

2. Class Description: Instance Enumeration

– Defines a class as an exhaustive enumeration of individuals that form the extension the set of instances of the class

– No new instances can be added to the class extension

– **owl:oneOf ({a1, a2, … an})**

OWL class JazzGenre collects all types of Jazz Music

```
<owl:Class rdf:about="http://dbpedia.org#JazzGenre”>
  <owl:oneOf rdf:parseType=”Collection">
    <owl:Thing rdf:about="http://dbpedia.org#AcidJazz"/>
    <owl:Thing rdf:about="http://dbpedia.org#Avant-GardeJazz"/>
    <owl:Thing rdf:about="http://dbpedia.org#BigBand"/>
    <owl:Thing rdf:about="http://dbpedia.org#BlueNote"/>
    <owl:Thing rdf:about="http://dbpedia.org#ContemporaryJazz"/>
    <owl:Thing rdf:about="http://dbpedia.org#CrossoverJazz"/>
    <owl:Thing rdf:about="http://dbpedia.org#Dixieland"/>
    <owl:Thing rdf:about="http://dbpedia.org#Fusion"/>
    <owl:Thing rdf:about="http://dbpedia.org#MainstreamJazz"/>
    <owl:Thing rdf:aabout="http://dbpedia.org#SmoothJazz"/>
  </owl:oneOf>
</owl:Class>
```

Not used in OWL Lite!

3. Class Description: Property Restrictions

- Describe an anonymous class, namely a class of all individuals that satisfy the restriction
- OWL distinguishes among
  - cardinality constraints
    - Max: ≤nR, Min: ≥nR, Equal: =nR
    - OWL Lite: only cardinalities of `0` and `1` are allowed
  - range constraints
    - $\exists$RC $\forall$RC
- Local Constraints
  - they apply to the properties of the instances of concerned classes

```
<owl:Restriction>
 <owl:onProperty rdf:resource="property"/>
    Constraint Expression
</owl:Restriction>
```

General Form of Property Restriction

Cardinality Constraints

- Define a class based on the number of values taken by a property
  - owl:cardinality: property *P* has *exactly n values* (=nR)

A string quartet has exactly 4 members

```
<owl:Class rdf:about="http://dbpedia.org#StringQuartet">
  <owl:equivalentClass>
    <owl:Restriction>
      <owl:onProperty rdf:resource="http://dbpedia.org#hasMembers"/>
        <owl:cardinality>4</owl:cardinality>
      </owl:Restriction>
  </owl:equivalentClass>
</owl:Class>
```

Cardinality Constraints

- Define a class based on the number of values taken by a property
  - owl:maxCardinality: property *P* has *at most n values* (≤nR)
  - owl:minCardinality: property *P* has *at least n values* (≥nR)

A full sized orchestra has at least 70 and at most 100 members

```
<owl:Class about="http://dbpedia.org#FullSizedOrchestra">
  <owl:equivalentClass>
    <owl:Restriction>
      <owl:onProperty rdf:resource="http://dbpedia.org#hasMembers"/>
      <owl:minCardinality>70</owl:cardinality>
      <owl:maxCardinality>100</owl:cardinality>
    </owl:Restriction>
  </owl:equivalentClass>
</owl:Class>
```

(Local) Range Constraints

- Define a class based on the type of property values
- Different from global RDFS range constraints
  - owl:someValuesFrom: $\exists$ PC
    - Defines the class of individuals *x* for which there exist *at least one value y (instance of class C or of the specified data range)* such that *(x, y) is an instance of property P*
  - owl:allValuesFrom: $\forall$ PC
    - Defines a class of individuals *x* for which it holds that if the *pair (x,y) is an instance of P*, then *y* should be an instance of class *C* or a value in the *specified data range*

Can only be used with named classes or datatypes in OWL Lite

  - owl:hasValue: $\exists$ P.{V}
    - Defines a class of the individuals *x* that have as *value for property P*, *V* or one that is *equivalent to V*

Cannot be used in OWL Lite

owl:allValuesFrom

Members of a string quartet play one of violin, viola, cello, and double bass

```
<owl:Class rdf:about="http://dbpedia.org#StringQuartetMember">
  <owl:equivalentClass>
    <owl:Restriction>
      <owl:onProperty rdf:resource="http://dbpedia.org#playsInstrument"/>
      <owl:allValuesFrom>
        <owl:Class>
          <owl:oneOf rdf:parseType="Collection">
            <owl:Thing rdf:about="http://dbpedia.org#Violin"/>
            <owl:Thing rdf:about="http://dbpedia.org#Viola"/>
            <owl:Thing rdf:about="http://dbpedia.org#Cello"/>
            <owl:Thing rdf:about="http://dbpedia.org#DoubleBass"/>
          </owl:oneOf>
         </owl:Class>
       </owl:allValuesFrom>
    </owl:Restriction>
  </owl:equivalentClass>
</owl:Class>
```

owl:someValuesFrom & owl:hasValue

At least one of the members of a Jazz band plays the saxophone

```
<owl:Class rdf:about="http://dbpedia.org#JazzBandMember">
  <owl:equivalentClass>
    <owl:Restriction>
      <owl:onProperty rdf:resource="http://dbpedia.org#playsInstrument"/>
      <owl:someValuesFrom rdf:resource="http://dbpedia.org#Saxophone"/>
    </owl:Restriction>
  </owl:equivalentClass>
</owl:Class>
```

Violin is the instrument of a violinist

```
<owl:Class rdf:about="http://dbpedia.org#Violinist">
  <owl:equivalentClass>
    <owl:Restriction>
      <owl:onProperty rdf:resource=" http://dbpedia.org#playsInstrument"/>
      <owl:hasValue rdf:resource="http://dbpedia.org#Violin"/>
    </owl:Restriction>
  </owl:equivalentClass>
</owl:Class>
```

4. Class Descriptions through set operations

- Set Intersection: owl:intersectionOf
- Set Union: owl:unionOf
- Set Complementation: owl:complementOf
- owl:IntersectionOf
  - links *a class to a list of class descriptions*
  - describes an (anonymous) class whose *class extension* contains the individuals that belong to the *intersection* of all said class descriptions
- owl:unionOf
  - links *a class to a list of class descriptions*
  - describes an (anonymous) class whose *class extension* contains the individuals that belong to the *union* of all said class descriptions

4. Class Descriptions through set operations

- ✓ Set Intersection: owl:intersectionOf
- ✓ Set Union: owl:unionOf
- Set Complementation: owl:complementOf
- owl:complementOf
  - links a class to *precisely one class description*
  - describes a class for which the class extension contains exactly those individuals that do not belong to the class extension of said class description
  - analogous to *negation*

- ***Only owl:intersectionOf used in OWL Lite***
- ***Can be used with named classes and OWL restrictions only***

owl:intersectionOf

An all-female band is a band whose members are all female musicians

```
<owl:Class about="http://dbpedia.org#AllFemaleBand">
  <owl:equivalentClass>
    <owl:Class>
      <owl:intersectionOf rdf:parseType="Collection">
        <owl:Class rdf:about="http://dbpedia.org#Musician"/>
        <owl:Class>
          <owl:Restriction>
            <owl:onProperty rdf:about="gender"/>
             <owl:hasValue rdf:resource="female"/>
          </owl:Restriction>
        </owl:Class>
      </owl:intersectionOf>
    </owl:Class>
  </owl:equivalentClass>
</owl:Class>
```

owl:unionOf & owl:complementOf

a class for which the class extension contains three individuals, namely Tosca, Salome, and Turandot (assuming they are all different)

```
<owl:Class about="http://dbpedia.org#ItalianOpera">
  <owl:unionOf rdf:parseType="Collection">
    <owl:Class>
      <owl:oneOf rdf:parseType="Collection">
        <owl:Thing rdf:about="#Tosca" />
        <owl:Thing rdf:about="#Salome" />
      </owl:oneOf>
    </owl:Class>
    <owl:Class>
      <owl:oneOf rdf:parseType="Collection">
        <owl:Thing rdf:about="#Turandot" />
        <owl:Thing rdf:about="#Tosca" />
      </owl:oneOf>
    </owl:Class>
  </owl:unionOf>
</owl:Class>
```

Everything but an all-female band

```
<owl:Class about="http://dbpedia.org#NotAnAllFemaleBand">
  <owl:complementOf>
    <owl:Class rdf:about="http://dbpedia.org#AllFemaleBand>
  </owl:complementOf>
</owl:Class>
```

OWL Class Axioms

- Contain additional components that *state necessary and/or sufficient characteristics of a class*
- OWL contains *3 language constructs* for combining *class descriptions into class axioms*
  - C1 rdfs:subClassOf C2
  - C1 owl:equivalentClass C2
  - C1 owl:disjointWith C2

C1 rdfs:subClassOf C2

- Extension of class C1 is a *subset* of the extension of class C2
- For any class C1 there may be any number of rdfs:subClassOf axioms.
- subclass axioms provide partial definitions
  - they represent necessary but not sufficient conditions for establishing class membership of an individual

C1 rdfs:subClassOf C2

Traditional Italian opera is defined as a subclass of a class of operas that have as opera type either Opera Seria or Opera Buffa

```
<owl:Class rdf:ID="http://dbpedia.org#TraditionalItalianOpera">
  <rdfs:subClassOf rdf:resource="http://dbpedia.org#Opera"/>
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="http://dbpedia.org#hasOperaType"/>
      <owl:someValuesFrom>
        <owl:Class>
          <owl:oneOf rdf:parseType="Collection">
            <owl:Thing rdf:about="http://dbpedia.org#OperaSeria"/>
            <owl:Thing rdf:about="http://dbpedia.org#OperaBuffa"/>
          </owl:oneOf>
        </owl:Class>
      </owl:someValuesFrom>
    </owl:Restriction>
  </rdfs:subClassOf>
</owl:Class>
```

without an additional cardinality constraint,
Property "hasOperaType" could actually have both values

C1 rdfs:subClassOf C2

an operetta is a musical work, that has at least one librettist and is not an opera.

```
owl:Class rdf:ID="http://dbpedia.org#Operetta">
  <rdfs:subClassOf rdf:resource="http://dbpedia.org#MusicalWork"/>
  <rdfs:subClassOf>
    <owl:Restriction>
      <owl:onProperty rdf:resource="http://dbpedia.org#hasLibrettist" />
      <owl:minCardinality>1</owl:minCardinality>
    </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:subClassOf>
    <owl:Class>
      <owl:complementOf rdf:resource="http://dbpedia.org#Opera"/>
    </owl:Class>
  </rdfs:subClassOf>
</owl:Class>
```

- ***leaves open the possibility that there are other musical works that have a librettist and are not operas***
- ***Use of owl:equivalentClass to state that Operetta's are Operas***

C1 owl:equivalentClass C2

- extension of class description C1 is *exactly the same* as class extension of class description C2
  - both class extensions contain exactly the same set of individuals
- does not imply class equality
  - Use owl:sameAs construct to denote class equality
- axioms with owl:equivalentClass can also be used to define an enumerated class by linking a class identifier to an enumeration
- for any class C1 there may be any number of owl:equivalentClass axioms
- equivalent class axioms provide full definitions
  - they represent necessary and sufficient conditions for classes

C1 owl:equivalentClass C2

```
<owl:Class rdf:ID="http://dbpedia.org#DaPonteOperaOfMozart">
  <owl:equivalentClass>
    <owl:Class>
      <owl:oneOf rdf:parseType="Collection">
        <Opera rdf:about="http://dbpedia.org#Nozze_di_Figaro"/>
        <Opera rdf:about="http://dbpedia.org#Don_Giovanni"/>
        <Opera rdf:about="http://dbpedia.org#Cosi_fan_tutte"/>
      </owl:oneOf>
    </owl:Class>
  </owl:equivalentClass>
</owl:Class>
```

- *Operas that together represent the "Da Ponte operas of Mozart"*
- *Expressed using an enumeration of three instances*
- *State necessary and sufficient conditions for class membership through owl:equivalenceClass construct*

C1 owl:equivalentClass C2

```
<owl:Class rdf:ID="http://dbpedia.org#DaPonteOperaOfMozart">
  <owl:equivalentClass>
    <owl:Class>
      <owl:oneOf rdf:parseType="Collection">
        <Opera rdf:about="http://dbpedia.org#Nozze_di_Figaro"/>
        <Opera rdf:about="http://dbpedia.org#Don_Giovanni"/>
        <Opera rdf:about="http://dbpedia.org#Cosi_fan_tutte"/>
      </owl:oneOf>
    </owl:Class>
  </owl:equivalentClass>
</owl:Class>
```

Constructs owl:one of, owl:intersectionOf, owl:unionOf and owl:complementOf are used for defining equivalent classes

C1 owl:disjointWith C2

- owl:disjointWith: the class extensions of the two classes have no individuals in common
- Any class C1 can be associated to any number of other classes through owl:disjointWith axioms
- owl:disjointWith axioms provide partial definitions
  - they represent necessary but not sufficient conditions

Cannot be used in OWL Lite

C1 owl:disjointWith C2

```
<owl:Class rdf:about="http://dbpedia.org#MusicDrama">
  <owl:equivalentClass>
    <owl:Class>
      <owl:unionOf rdf:parseType="Collection">
        <owl:Class rdf:about="http://dbpedia.org#Opera"/>
        <owl:Class rdf:about="http://dbpedia.org#Operetta"/>
        <owl:Class rdf:about="http://dbpedia.org#Musical"/>
      </owl:unionOf>
    </owl:Class>
  </owl:equivalentClass>
</owl:Class>
```

```
<owl:Class rdf:about="http://dbpedia.org#Opera">
  <rdfs:subClassOf rdf:resource="http://dbpedia.org#MusicDrama"/>
</owl:Class>

<owl:Class rdf:about="http://dbpedia.org#Operetta">
  <rdfs:subClassOf rdf:resource="http://dbpedia.org#MusicDrama"/>
  <owl:disjointWith rdf:resource="http://dbpedia.org#Opera"/>
</owl:Class>

<owl:Class rdf:about="http://dbpedia.org#Musical">
  <rdfs:subClassOf rdf:resource="http://dbpedia.org#MusicDrama"/>
  <owl:disjointWith rdf:resource="http://dbpedia.org#Opera"/>
  <owl:disjointWith rdf:resource="http://dbpedia.org#Operetta"/>
</owl:Class>
```

OWL Properties

- Property extension a pair of (subject, object) elements
  - Not a single element: in relational terms it is a binary relation
- Properties have a direction, from domain to range
- Two types of properties
  - Object properties link individuals to individuals
  - Datatype properties link individuals to data values
- Built-in Classes:
  - owl:ObjectProperty: the class of properties whose value is an *individual*

```
<owl:ObjectProperty rdf:ID="http://dbpedia.org#instrument">
```

  - owl:DatatypeProperty: the class of properties whose value is an *atomic value*

```
<owl:DataTypeProperty rdf:ID="http://dbpedia.org#birthYear">
```

  - owl:ObjectProperty and owl:DatatypeProperty are *subclasse*s of the RDF class rdf:Property

OWL Property Axioms

- Used for defining additional characteristics for OWL Properties
  - Property Hierarchies
    - rdfs:subPropertyOf
  - Domain/Range Constraints
    - rdfs:range and rdfs:domain
  - Relations to other properties
    - owl:equivalentProperty and owl:inverseOf
  - Global Cardinality Constraints
    - owl:FunctionalProperty and owl:InverseFunctionalProperty
  - Logical Property Constraints
    - owl:SymmetricProperty and owl:TransitiveProperty

Property Hierarchies

- P1 rdfs:subPropertyOf P2
  - property extension of P1 should be a subset of the property extension of P2

all instances of the property "musicFusionGenre" are also members of property "overlaps".

```
<owl:ObjectProperty rdf:ID="http://dbpedia.org#musicFusionGenre">
  <rdfs:subPropertyOf rdf:resource="http://dbpedia.org#overlaps"/>
</owl:ObjectProperty>
```

Domain/Range Constraints

- P1 rdfs:domain C1
  - asserts that the subjects of instances of property P1 must belong to the extension of class C1
  - links a property P1 to one or more class descriptions C
  - when multiple rdfs:domain axioms for property P exist
    - restrict the domain of the property to those individuals that belong to the intersection of the class descriptions
  - when multiple classes should act as domain, one must use owl:unionOf

Domain/Range Constraints

- P1 rdfs:range C1
  - asserts that the objects of instances of property P1 must belong to the extension of class C1
  - links a property P to one or more class descriptions C or a data range
  - when multiple rdfs:range axioms for property P exist
    - restrict the range of the property to those individuals that belong to the intersection of the class descriptions
  - when multiple classes should act as range , one must use owl:unionOf

Domain/Range Constraints

"musicFusionGenre" is a subproperty of "overlaps", defined in and takes its value from class "MusicGenre"

```
<owl:ObjectProperty rdf:ID="http://dbpedia.org#musicFusionGenre">
  <rdfs:subPropertyOf rdf:resource="http://dbpedia.org#overlaps"/>
  <rdfs:domain rdf:resource="http://dbpedia.org#MusicGenre"/>
  <rdfs:range rdfs:resource="http://dbpedia.org#MusicGenre"/>
</owl:ObjectProperty>
```

Value Constraints vs RDFS Constraints

- owl:allValuesFrom, owl:someValuesFrom are local and enforced on the property when applied to that class
- rdfs:range and rdfs:domain constraints are global and apply to all instances of the properties irrespective to the class in which it is applied

Relations to other properties

- P1 owl:equivalentProperty P2
  - Properties P1 and P2 have the same set of instances
  - Property equivalence is not property equality
    - Equivalent properties have the same instances, but may have different intentional meaning (i.e., denote different concepts).
- P1 owl:inverseOf P2
  - *Recall: Properties have a direction, from domain to range.*
  - owl:inverseOf construct can be used to define an inverse relation between properties

Relations to other properties

```
<owl:ObjectProperty rdf:ID="http://dbpedia.org#musicComposer">
  <rdfs:subPropertyOf rdf:resource="http://dbpedia.org#coParticipatesWith"/>
  <rdfs:domain rdf:resource="http://dbpedia.org#Work"/>
  <rdfs:range rdf:resource="http://dbpedia.org#MusicalArtist"/>
  <owl:equivalentProperty rdf:resource="http://dbpedia.org#musicBy"/>
  <owl:inverseOf rdf:resource="http://dbpedia.org#composed"/>
</owl:ObjectProperty>
```

- *"musicComposer" is a subproperty of "coParticipatesWith"*
- *defined in class Work*
- *takes its values from class "MusicalArtist"*
- *equivalent to property "musicBy"*
- *inverse of property "composed"*

Global Cardinality Constraints

- P1 rdf:type owl:FunctionalProperty
  - A resource *x*, can have only one (unique) value *y* for property P1
    - If P is a functional property there cannot be two distinct values y1 and y2 such that the pairs (x,y1) and (x,y2) are both instances of this property
  - Both *object* and *datatype properties* can be functional

```
<owl:DataTypeProperty rdf:ID="http://dbpedia.org#birthDate">
  <rdf:type rdf:resource="&owl;FunctionalProperty"/>
  <rdfs:domain rdf:resource="http://dbpedia.org#Person"/>
  <rdfs:range rdf:resource="&xsd;date"/>
  <owl:equivalentProperty rdf:resource="http://schema.org#DateOfBirth"/>
</owl:DataTypeProperty>
```

- *a person has a unique birthdate*
- *property birthDate is equivalent to property DateOfBirth*

Global Cardinality Constraints

- P1 rdf:type owl:InverseFunctionalProperty
  - A resource *x*, is uniquely determined by the *object* y of property P1
  - if P is an inverse functional property there cannot be two distinct instances x1 and x2 such that both pairs (x1,y) and (x2,y) are instances of P.

```
<owl:ObjectProperty rdf:ID="http://dbpedia.org#SSN">
  <rdf:type rdf:resource="&owl;InverseFunctionalProperty"/>
  <rdfs:domain rdf:resource="http://dbpedia.org#Person"/>
  <rdfs:range rdf:resource="&xsd;nonNegativeInteger"/>
</owl:ObjectProperty>
```

- *a person is uniquely identified by her SSN number*

Cannot be used in OWL Lite/DL

Logical Characteristics of Properties

- P1 owl:TransitiveProperty P2
  - If *(x, y)* and *(y, z)* is are *instances of property* transitive property *P* then we can infer that the pair *(x,z)* is also an instance of property P

```
<owl:ObjectProperty rdf:ID="http://dbpedia.org#subEvent">
  <rdf:type rdf:resource="&owl;TransitiveProperty"/>
  <rdfs:domain rdf:resource="http://dbpedia.org#MusicEvent"/>
  <rdfs:range rdf:resource="http://dbpedia.org#MusicEvent"/>
</owl:ObjectProperty>
```

"subEvent" is a transitive property, whose domain and range is class "MusicEvent"

Logical Characteristics of Properties

- P1 rdf:type owl:SymmeticProperty
  - If *P* is a *symmetric property* and if a pair *(x,y)* is an *instance of P*, and the pair *(y,x)* is *also instance of P*

```
<owl:ObjectProperty rdf:ID="http://dbpedia.org#playedWith">
  <rdf:type rdf:resource="&owl;SymmetricProperty"/>
  <rdfs:domain rdf:resource="http://dbpedia.org#MusicArtist"/>
  <rdfs:range rdf:resource="http://dbpedia.org#MusicArtist"/>
</owl:ObjectProperty>
```

OWL2

- OWL1 was based on techniques that allowed decidable, sound and complete reasoning in DL languages
- OWL1 contained 3 species of OWL
  - OWL Full: an extension of RDF to give semantics to OWL keywords
    - Intended to behave "similar" to OWL DL but applicable to all RDF documents
    - Entailment problem undecidable (if the semantics is non-contradictory)
  - OWL DL: a DL-based KR language with an RDF syntax
    - Not all RDF documents are OWL DL ontologies
  - OWL Lite: a restricted version of OWL DL
- OWL2: OWL 2 DL and OWL Full to extended OWL 1 family of languages
  - Syntactic Sugar (easiness in writing statements)
  - Constructs for increased expressivity
  - Datatype support
  - Metamodelling
  - Annotation

OWL2: Disjoint Classes/Properties

- OWL1: allows us to specify that 2 classes/properties are disjoint
- OW2: allows us to state that classes/properties in a set of classes/properties are pairwise disjoint

```
<owl:AllDisjointClasses>
   <owl:members rdf:parseType="Collection">
     <owl:Class rdf:about=”&example;C1"/>
     <owl:Class rdf:about=”&example;C2"/>
     <owl:Class rdf:about=“&example;C3”/>
   </owl:members>
</owl:AllDisjointClasses>
```

```
<owl:AllDisjointProperties>
  <owl:members rdf:parseType="Collection">
    <owl:ObjectProperty rdf:about=”&example;P1"/>
    <owl:ObjectProperty rdf:about=”&example;P2"/>
    <owl:ObjectProperty rdf:about=”&example;P3"/>
  </owl:members>
</owl:AllDisjointProperties>
```

OWL2: Property Characteristics

- P1 rdf:type owl:ReflexiveProperty
  - For an instance *x*, and *reflexive property P*, then *(x,x)* is *an instance of property P*

```
<owl:ReflexiveProperty rdf:about="&example;sameAgeAs">
```

- P1 rdf:type owl:IrreflexiveProperty
  - For an instance *x*, and *irreflexive property P*, then *(x,x) is not an instance of property P*

```
<owl:IrreflexiveProperty rdf:about="&example;strictlyTallerThan">
```

OWL2: Property Characteristics

- P1 rdf:type owl:AsymmetricProperty
  - For an instance *(x,y)* of an *asymmetric property P*, then *(y,x)* is *not an instance of property P*

```
<owl:AsymmetricProperty rdf:about="&example;strictlyTallerThan"/>
```

- P1 owl:propertyDisjointWith P2
  - For an instance *(x,y) of property P1*, then *(x,y) cannot be an instance of property P2*

```
<owl:ObjectProperty rdf:about="&example;connectedTo">
  <owl:propertyDisjointWith rdf:resource="&example;contiguousWith"/>
</owl:ObjectProperty>
```

```
<owl:AsymmetricProperty rdf:about="&example;strictlyTallerThan">
```

OWL2: Self Restriction

- owl:hasSelf: Defines *a class of individuals* which are *related to themselves through a specific property*

People who we have committed suicide

```
<owl:Class rdf:about="http://dbpedia.org#MusiciansCommittedSuicide">
  <owl:equivalentClass>
    <owl:Restriction>
      <owl:onProperty rdf:resource="http://dbpedia.org#killed"/>
      <owl:hasSelf rdf:resource="&xsd;boolean"/>
    </owl:Restriction>
  </owl:equivalentClass>
</owl:Class>
```

OWL2: Quantified Cardinality Restrictions

- OWL1 lets us specify the local range of a property or the number of values taken by the property
- OWL2 allows us to specify both

A full sized orchestra has at least 70 and at most 100 members

```
<owl:Class about="http://dbpedia.org#FullSizedOrchestra">
  <owl:equivalentClass>
    <owl:Restriction>
      <owl:onProperty rdf:resource="http://dbpedia.org#hasMembers"/>
      <owl:onClass rdf:resource="http://dbpedia.org#Person"/>
      <owl:minCardinality>70</owl:cardinality>
      <owl:maxCardinality>100</owl:cardinality>
    </owl:Restriction>
   </owl:equivalentClass>
</owl:Class>
```

Similar construct can be used for datatype properties!

OWL2: Property Chain Axioms

- *Allow one to infer the existence of a property from a chain of properties*
  - If *(x,y)* is an *instance of property P1* and *(y,z)* is an *instance of property P2*, then *(x,y)* is an instance of *property P3*

```
<rdf:Description rdf:about="isInfluencedBy">
  <owl:propertyChainAxiom rdf:parseType="Collection">
    <owl:ObjectProperty rdf:about="http://dbpedia.org#influencedBy"/>
    <owl:ObjectProperty rdf:about="http://dbpedia.org#influencedBy"/>
  </owl:propertyChainAxiom>
</rdf:Description>
```

```
<rdf:Description rdf:about="hasEnemy">
  <owl:propertyChainAxiom rdf:parseType="Collection">
    <owl:ObjectProperty rdf:about="http://dbpedia.org#hasEnemy"/>
    <owl:ObjectProperty rdf:about="http://dbpedia.org#hasFriend"/>
  </owl:propertyChainAxiom>
</rdf:Description>
```

OWL2: Property Chain Axioms

- *Arbitrary property chain axioms* may lead to *undecidability*
- *Restriction*: set of property chain axioms must *be regular*
  - There must be a *strict linear order on the properties*
  - Every property chain axiom has to have one of the following forms:

1	R(x,y) and R(y,z) then R(x,z)
2	R(y1,y2) and S1(y3,y3) and … Sn (yn-1,yn) then R(y1,yn)
3	S1(y1,y2) and S2(y2,y3) and … Sn(yn-1,yn) then R(y1, yn)
4	S1(y1,y2) and S2(y2,y3) and … Sn(yn-1,yn) then R(y1, yn)
5	S(y1,y2) and S(y2,y1) then R(y1,y2)

OWL2: Property Chain Axioms

1	R(x,y) and R(y,z) then R(x,z)
2	R(y1,y2) and S1(y3,y3) and … Sn (yn-1,yn) then R(y1,yn)
3	S1(y1,y2) and S2(y2,y3) and … Sn(yn-1,yn) then R(y1, yn)
4	S1(y1,y2) and S2(y2,y3) and … Sn(yn-1,yn) then R(y1, yn)
5	S(y1,y2) and S(y2,y1) then R(y1,y2)

- Example (1):
  - R(y1,y2) and R(y2,y3) then R(y1,y3)
  - S(y1,y2) and S(y2,y3) then S(y1,y3)
  - R(y1,y2) and S(y2,y3) and R(y3,y4) then T(y1,y4)

  Regular Order S < R < T
- Example (2)
  - R(y1,y2) and T(y2,y3) and S(y3,y4) then T(y1,y4)

  Does not comply to a form
- Example (3)
  - R(y1,y2) and S(y2,y3) then S(y1,y3)
  - S(y1,y2) and R(y2,y3) then R(y1,y3)

  No regular order exists

OWL2: Property Chain Axioms

- *Combining property chain axioms* and *cardinality constraints* may lead to *undecidability*
- *Restriction*: use only simple properties in cardinality expressions (i.e, those that cannot be directly or indirectly inferred from property chains)
- Technically:
  - For any property chain axiom S1(y1,y2) and S2(y2,y3) and … Sn(yn-1,yn) then R(y1, yn) then n>1, then *R is not a simple property*
  - For any *sub-property chain axiom S*, then *R is not a simple property*
  - *All other properties are simple*
- Example
  - Q(y1,y2) and P(y2,y3) then R(y1,y3)
  - R(y1,y2) and P(y2,y3) then R(y1,y3)
  - R rdfs:subPropertyOf S
  - P rdfs:subPropertyOf R
  - Q rdfs:subPropertyOf S

Non-simple R, S
Simple P, Q

Data Integration in OWL2

- Practical problem: given ontologies from different sources, which identifiers refer to the same individuals?
- Typical approaches in OWL:
  - Explicitly specify equality (owl:sameAs)
  - Use inverse functional properties ("same values → same individual")
- Problems:
  - equality requires explicit mappings (rare on the Web)
  - OWL DL disallows inverse functional datatype properties (complicated interplay with datatype definitions!)
  - Only one property used globally for identification, no property combinations (Example: "All participants in a music album with the same name and birthday are the same.")

Data Integration in OWL2

- OWL2 provides a way to model keys!
  - "All participants in a music album with the same name and birthday are the same."
  - Expressed in the form of keys ➔owl:hasKey
- Restriction: Keys apply only to named individuals – objects of the interpretation domain to which a constant symbol refers

```
<owl:Class rdf:about="Person">
   <owl:hasKey rdf:parseType="Collection">
     <owl:ObjectProperty rdf:about="hasSSN">
   </owl:hasKey>
 </owl:Class>
```

OWL Reasoning

- A reasoner makes use of the information asserted in the ontology.
- Based on the semantics described, a reasoner can help us to discover inferences that are a consequence of the knowledge that we've presented that we weren't aware of beforehand.
- Is this new knowledge?
  - What's actually in the ontology?

OWL Reasoning

- Subsumption reasoning
  - Allows us to infer when one class is a subclass of another
  - B is a subclass of A if it is necessarily the case that (in all models), all instances of B must be instances of A.
  - This can be either due to an explicit assertion, or through some inference process based on an intentional definition.
  - Can then build concept hierarchies representing the taxonomy.
  - This is classification of classes.
- Satisfiability reasoning
  - Tells us when a concept is unsatisfiable
    - i.e. when there is no model in which the interpretation of the class is non-empty.
  - Allows us to check whether our model is consistent.

Reasoning

- Reasoning can be used as a design support tool
  - Check logical consistency of classes
  - Compute implicit class hierarchy
- May be less important in small local ontologies
  - Can still be useful tool for design and maintenance
  - Much more important with larger ontologies/multiple authors
- Valuable tool for integrating and sharing ontologies
  - Use definitions/axioms to establish inter-ontology relationships
  - Check for consistency and (unexpected) implied relationships
- For most DLs, the basic inference problems are decidable (e.g. there is some program that solves the problem in a finite number of steps)

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  - *Pascal Hitzler, Markus Krötzsch, Sebastian Rudolph:* Knowledge Representation for the Semantic Web (Part I: OWL 2)
  - W3C, OWL Features: Available at *http://www.w3.org/TR/owl-features/*