Welcome to INFO216: Knowledge Graphs

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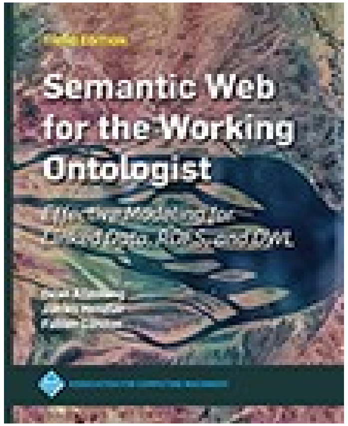
Session 9: Ontologies (OWL)

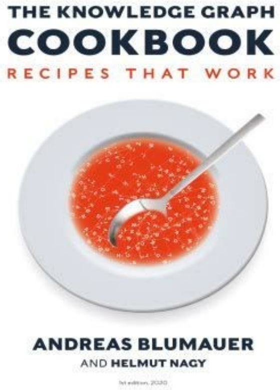
- Themes:
  - what and why?
  - basic OWL constructs (“RDFS-Plus”):
    - more precise properties
    - sameness and difference
    - complex classes
  - more advanced OWL
    - restriction classes
  - Programming in RDFLib

Readings

- Sources:
  - Allemang, Hendler, Gandon (2020):
    Semantic Web for the Working Ontologist, 3rd edition:
    chapter 9-10 (“RDFS Plus”, chapters 8-9 in the 2nd ed.)

    advanced: chapters 12-13 (chapters 11-12 in the 2nd ed.)
  - Blumauer & Nagy (2020):
    Knowledge Graph Cookbook – Recipes that Work:
    e.g., pages 105-109, 123-124, *(supplementary)*
- Resources in the wiki <http://wiki.uib.no/info216>:
  - OWL 2 Primer, sections 2-6 *(advanced: 9-10)*:
    http://www.w3.org/TR/owl-primer/
    - show: Turtle
  - VOWL: Visual Notation for OWL Ontologies





Web Ontology Language (OWL)

Why do we need vocabularies?

- Shared, well-defined terms (dereferencable URIs) for types, properties and some individuals that can be used to represent a domain
- Domains can be:
  - people, their friends and workplaces (FOAF, BIO)
  - electronic and other documents (DC, BIBO)
  - commerce (schema.org)
  - classification in libraries etc. (SKOS)
  - general encyclopedic information (DBpedia, Wikidata)
  - general time and place (OWL-Time, geo)
  - ...and *lots* of others (→S10)

Why do we need vocabularies?

- To make knowledge graphs more precisely defined
- To make semantic data sets easier to use
  - encourage reuse
  - avoid misunderstandings and errors
  - easier to understand, recombine, enrich...
- To support computer processing
  - more powerful
  - more general

RDFS is a useful starting point...

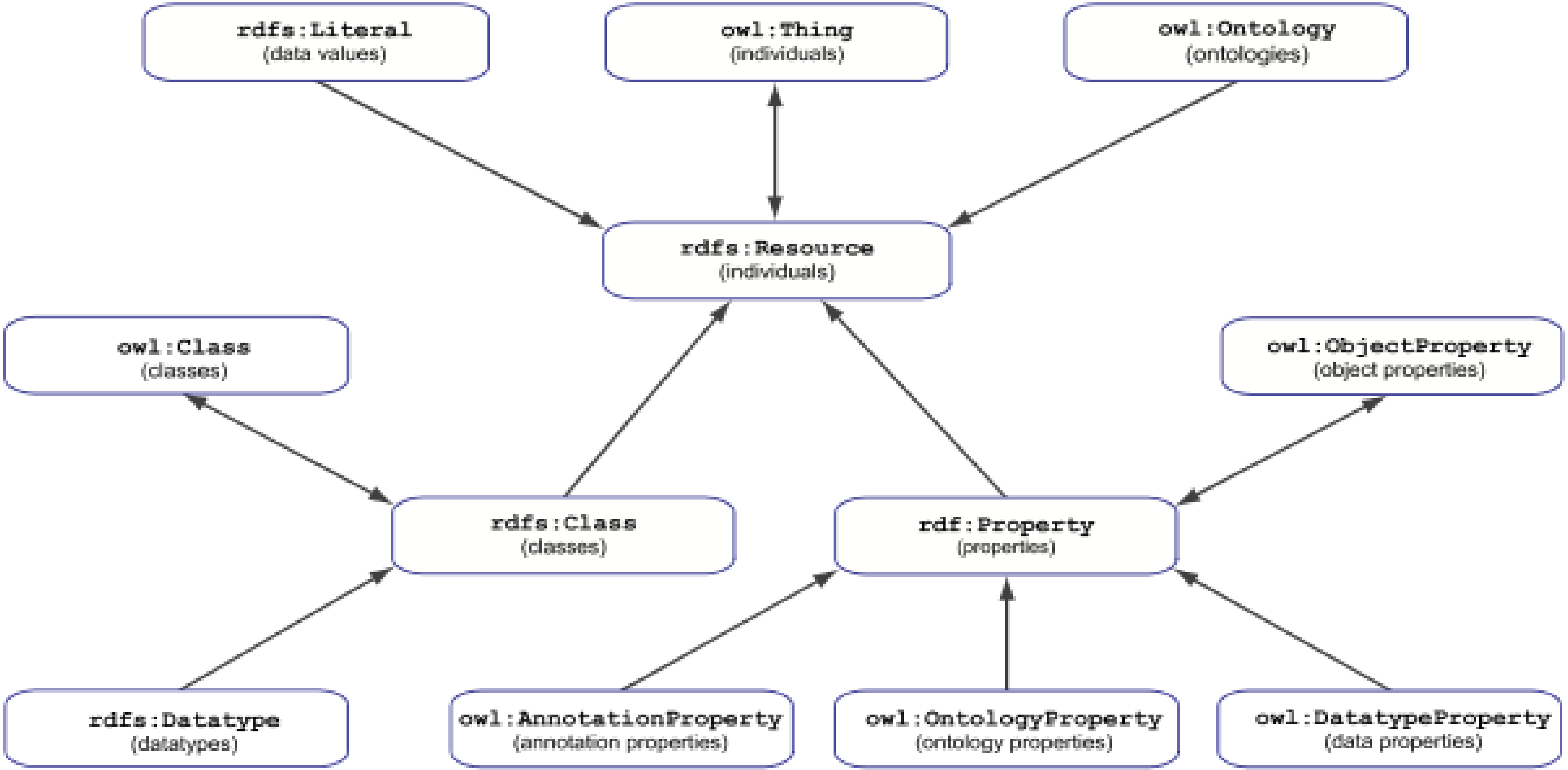
- We can say:
  - “a president is a politician” so that
    - saying “Trump is a president” entails saying “Trump is a politician”
  - “a politician is a human” so that
    - saying “Trump is a president” *also* entails saying “Trump is a human”
  - “the president of something is a politician” so that
    - saying “Trump is a president of U.S.A.” entails “saying Trump is a politician”
  - “something having a president is a country” so that
    - saying “Trump is a president of U.S.A.” entails saying “U.S.A. is a country”
  - “being president also means being citizen” so that
    - saying “Trump is a president of U.S.A.” entails
      saying “Trump is a citizen of U.S.A.”
- *RDFS expresses this but not (so much) more...*

RDFS is a useful starting point...

- But lots of simple stuff it cannot express, e.g.:
  - “every ancestor of an ancestor is an ancestor too”
  - “the BirthNumber of a Person is unique”
  - “a Republic has exactly one President”
  - “a FootballTeam has 11 activePlayers, a VolleyballTeam 6”
  - “a StringQuartet has two violins but only one viola and one cello”
  - “classes with different URIs actually represent the same class”
  - “resources with different URIs represent the same resource”
  - “properties with different URIs are actually the same”
  - “two individuals are different”, “two classes are disjoint”
  - “a class is a union (or intersection) of other classes”
  - “a class is a negation of another class”
- *OWL expresses all this and more!*

Basic idea

- Web Ontology Language (OWL):
  - *builds* on RDF and RDFS
  - *reuses*, *renames* and *specialises* classes and properties from RDFS
  - *adds* precision and formality
- Basic OWL-concepts:
  - owl:Thing (equivalent to rdfs:Resource)
  - owl:Class (equivalent to rdfs:Class)
  - owl:ObjectProperty (equivalent to rdf:Property)
  - owl:NamedIndividual (things with URIs and that are not classes)
- Good practice: keep *Classes, Individuals, and Properties disjoint*, i.e., no resource has more than one of them as *rdf:type*



http://www.w3.org/TR/owl2-rdf-based-semantics/

What does OWL offer?

- Extensions of RDFS, e.g.:
  - more *specific types* of properties
  - *identical and different* classes, properties, individuals
  - *defining new classes*:
    - complex classes (union, intersection, complement)
    - property restrictions, enumeration of individuals
  - *defining new properties* based on existing ones
  - *mathematical formality* (for large parts of OWL)
    - (more on this later)

Reuses or specialises RDFS

- *Reused* in OWL:
  - rdf:type, rdf:Property, rdfs:subClassOf, rdfs:subPropertyOf, rdfs:domain, rdfs:range
  - ...and lots of other stuff...
- *Renamed* by OWL:
  - owl:Thing (equivalent to rdfs:Resource)
  - owl:Class (equivalent to rdfs:Class)
  - owl:ObjectProperty (equivalent to rdf:Property)
- *Specialised* by OWL:
  - everything else in OWL *specialises* something in RDF / RDFS
  - but also introduces its own, and more powerful, formal underpinning

Basic OWL
("RDFS Plus")

Inverse properties

- Properties can be inverses (or reverses) of one another, e.g.,
  - ex:DonaldTrump ex:presidentOf ex:USA .
  - ex:USA ex:hasPresident ex:DonaldTrump .
- P1 owl:inverseOf P2:
  - ex:presidentOf owl:inverseOf ex:hasPresident .
  - owl:inverseOf owl:inverseOf owl:inverseOf .
  - owl:inverseOf a owl:ObjectProperty .
- Entailment rules:
  - if *P1 owl:inverseOf P2* then
    - *P2 owl:inverseOf P1 .*
  - if *S P1 O . P1 owl:inverseOf P2* then
    - O P2 S .

The axioms are informative (not mandatory)

Symmetric properties

- Some properties are their own inverse, e.g.,
  - ex:DonaldTrump ex:marriedTo ex:MelianiaTrump .
  - ex:MelianiaTrump ex:marriedTo ex:DonaldTrump .
- P rdf:type owl:SymmetricProperty:
  - ex:marriedTo a owl:SymmetricProperty .
  - owl:inverseOf a owl:SymmetricProperty .
  - owl:SymmetricProperty rdfs:subClassOf owl:ObjectProperty .
- Entailment rules:
  - if *P a owl:SymmetricProperty* then
    - P owl:inverseOf P .
  - if *S P O . P a owl:SymmetricProperty* then
    - O P S .

The axioms are informative (not mandatory)

Asymmetric, reflexive, irreflexive properties

- New in OWL2:
  - both *symmetric* and *asymmetric* properties:
    - ex:marriedTo a owl:SymmetricProperty .
      - "marriage is always mutual (two-way)"
    - ex:hasChild a owl:AsymmetricProperty .
      - "two resources cannot be the child of each other"
    - *many properties are neither – leave it open!*
  - both *reflexive* and *irreflexive* properties:
    - owl:sameAs a owl:ReflexiveProperty .
      - "every resource is the same as itself"
    - ex:hasChild a owl:IrreflexiveProperty .
      - "no resource can be its own child"
    - *many properties are neither – leave it open!*

Transitive properties

- Some properties can form chains so that the result is the property itself, e.g.:
  - ex:DonaldTrump ex:hasPredecessor ex:BarackObama .
  - ex:BarackObama ex:hasPredecessor ex:GeorgeWBush .
  - ex:DonaldTrump ex:hasPredecessor ex:GeorgeWBush .
- P a owl:TransitiveProperty:
  - ex:hasPredecessor a owl:TransitiveProperty .
  - rdfs:subClassOf a owl:TransitiveProperty .
  - rdfs:subPropertyOf a owl:TransitiveProperty .
- Entailment rules:
  - “if *S P X . X P O . P a owl:TransitiveProperty* then
    - S P O .”

The axioms are informative (not mandatory)

Functional properties

- Each subject *can only have one* object value for the functional property, e,g.,
  - ex:hasPresident a owl:FunctionalProperty .
  - ex:dateOfBirth a owl:FunctionalProperty .
  - owl:FunctionalProperty rdfs:subClassOf owl:ObjectProperty .
- Entailment rule:
  - if *S P O1 . S P O2 . P a owl:FunctionalProperty* then
    - *O1 owl:sameAs O2 .*
  - The rule also holds for *owl:DatatypeProperties*, but:
    - if two different literals become asserted as *owl:sameAs* one another, *the ontology is inconsistent*

Functional properties

- Each subject *can only have one* object value for the functional property, e,g.,
  - ex:hasPresident a owl:FunctionalProperty .
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  - owl:FunctionalProperty rdfs:subClassOf owl:ObjectProperty .
- Entailment rule:
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    - *O1 owl:sameAs O2 .*

!

  - The rule also holds for *owl:DatatypeProperties*, but:
    - if two different literals become asserted as *owl:sameAs* one another, *the ontology is inconsistent*

Inverse functional properties

- Two different subjects cannot have the same object for an inverse functional property, i.e.,
  - ex:presidentOf a owl:InverseFunctionalProperty .
- Entailment rule:
  - if *S1 P O . S2 P O . P a owl:InverseFunctionalProperty* then
    - *S1 owl:sameAs S2 .*
- Inverse functional properties are *unique* for each individual
  - used for *identifiers*
  - OWL 2 also has a built-in *owl:hasKey* property for identifiers

Summary: more precise properties

- owl:inverseOf
- owl:SymmetricProperty, owl:AsymmetricProperty
- owl:ReflexiveProperty, owl:IrreflexiveProperty
- owl:TransitiveProperty
- owl:FunctionalProperty, owl:InverseFunctionalProperty
- owl:hasKey
- Also:
  - negated properties
  - chained properties, e.g.:

```
fam:hasGrandmother
        owl:propertyChainAxiom
                ( :hasParent  :hasMother ) .
```

Individual equivalence

- Sometimes, two individuals (with different URI-s) represent the same thing:
  - http://dbpedia.org/resource/Donald_Trump
  - http://wikidata.org/entity/Q22686
- I1 owl:sameAs I2:
  - owl:sameAs a owl:ReflexiveProperty .
  - owl:sameAs a owl:SymmetricProperty .
  - owl:sameAs a owl:TransitiveProperty .
- owl:sameAs is an *equivalence relation*:
  - because it is *reflexive*, *symmetric* and *transitive*

The axioms are informative (not mandatory)

Unique Name Assumption (UNA)

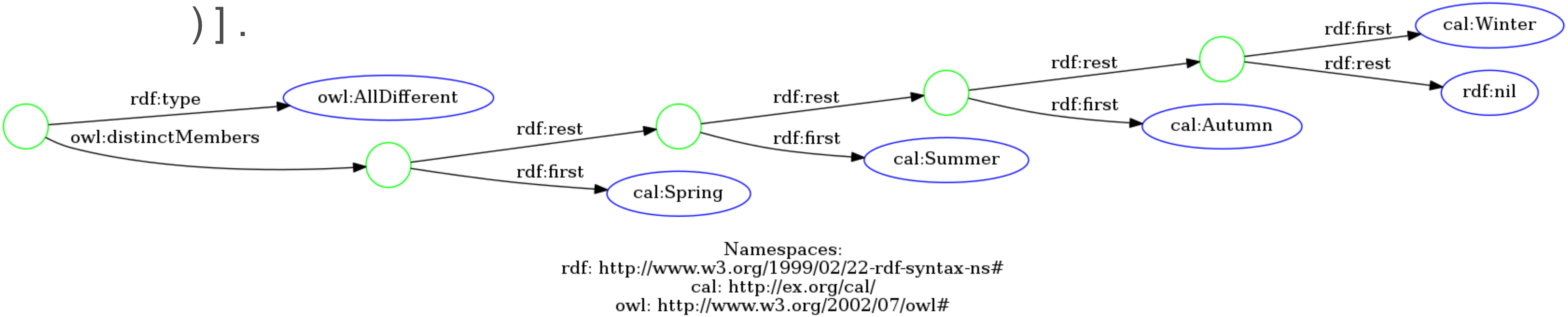
- If two resources have different names, do they necessarily represent different things?
- RDF and OWL does *not* assume this!
  - *in RDF and OWL, we do not know whether resources with different names represent different things or not*
- We can use
  - owl:sameAs – two resources represent the same thing
  - owl:differentFrom – they represent different things
  - ...or we can leave it open
- Some ICT-languages and technologies use UNA, others do not!

Individual difference

- Sometimes, a *pair* of individuals with different names (URI-s) represent *different* things, e.g.,
  - cal:Spring owl:differentFrom cal:Summer .
- owl:differentFrom
  - *not* transitive
  - *not* reflexive

Individual difference

- Sometimes, a pair of individuals with different names (URI-s) represent different things, e.g.,
  - cal:Spring owl:differentFrom cal:Summer .
- Sometimes, a *group* of individuals with different names (URI-s) *all* represent *different* things, e.g.,
  - [a owl:AllDifferent ;
    owl:distinctMembers (
    cal:Spring cal:Summer cal:Autumn cal:Winter
)] .



https://www.ldf.fi/service/rdf-grapher

Individual difference

- Sometimes, a pair of individuals with different names (URI-s) represent different things, e.g.,
  - cal:Spring owl:differentFrom cal:Summer .
- Sometimes, a group of individuals with different names (URI-s) all represent different things, e.g.,
  - [a owl:AllDifferent ;
    owl:distinctMembers (
    cal:Spring cal:Summer cal:Autumn cal:Winter
)] .
  - *owl:AllDifferent* and *owl:distinctMembers* are special constructs in OWL
    - they must always be used together
  - ...corresponds to pairwise *owl:differentFrom* between *all* individuals in the *owl:distinctMembers*-list

Equivalent classes

- Sometimes, two classes (with different URI-s) represent the *same* class:
- C1 owl:equivalentClass C2:
  - owl:equivalentClass a owl:ReflexiveProperty .
  - owl:equivalentClass a owl:SymmetricProperty .
  - owl:equivalentClass a owl:TransitiveProperty .
- owl:equivalentClass is another *equivalence relation*:
    - it is *reflexive*, *symmetric* and *transitive*
- C1 owl:equivalentClass C2 means the same as
  - *C1 rdfs:subClassOf C2* and *C2 rdfs:subClassOf C1*
- *Also disjoint classes:*
    - *uib:InternalCensor*
      owl:disjointWith skos:ExternalCensor .

The axioms are informative (not mandatory)

Equivalent properties

- Two properties (with different URI-s) can represent the same property:
- P1 owl:equivalentProperty P2:
  - owl:equivalentProperty a owl:ReflexiveProperty .
  - owl:equivalentProperty a owl:SymmetricProperty .
  - owl:equivalentProperty a owl:TransitiveProperty .
- owl:equivalentProperty is another *equivalence relation*:
    - it is *reflexive*, *symmetric* and *transitive*
- *Also disjoint properties:*
    - skos:prefLabel owl:propertyDisjointWith skos:altLabel .

The axioms are informative (not mandatory)

Summary: sameness and difference

- Individuals:
  - pairwise: owl:sameAs, owl:differentFrom
  - groupwise difference: owl:AllDifferent
- Classes:
  - pairwise: owl:equivalentClass, owl:disjointWith
  - groupwise difference: owl:AllDisjointClasses
- Properties:
  - pairwise: equivalentProperty, propertyDisjointWith
  - groupwise difference: owl:AllDisjointProperties
- Membership in the groups:
  - owl:distinctMembers *(preferred)* or owl:members

Basic OWL reasoning in Python and rdflib

Basic OWL inference in RDFLib

- ```
  import owlrl
  ...

  DeductiveClosure(RDFS_Semantics).expand(graph)       # RDFS reasoning
  ...

  DeductiveClosure(OWLRL_Semantics).expand(graph)    # OWL-RL reasoning
  ...

  DeductiveClosure(OWLRL_Extension,                   # Maximum reasoning
          rdfs_closure = True, axiomatic_triples = True,
          datatype_axioms = True).expand(graph)
  ...
  ```
  ```

Complex OWL classes

Union classes

Actually, FOAF defines more types of Agents than this!

- A union class contains all the individuals in *either of* two or more other classes, e.g.,
  - foaf:Agent
    a owl:Class;
    owl:unionOf (foaf:Person foaf:Organization) .
- Entailment rule:
  - if *C owl:equivalentClass [owl:unionOf (C1... Cn)]* then
    - C1 rdfs:subClassOf C . ... Cn rdfs:subClassOf C .
- why not say just, e.g.,:
  - foaf:Person rdfs:subClassOf foaf:Agent .
  - foaf:Organization rdfs:subClassOf foaf:Agent .

?

Intersection classes

- An intersection class contains all the individuals in *all of* two or more other classes, e.g.
  - uib:StudentAssistant
    a owl:Class;
    owl:intersectionOf (uib:Student uib:Teacher) .
- Entailment rule:
  - if *C owl:equivalentClass [owl:intersectionOf (C1... Cn)]* then
    - C rdfs:subClassOf C1 . ... C rdfs:subClassOf Cn .
- why not say, e.g.:
  - uib:StudentAssistant rdfs:subClassOf uib:Student .
  - uib:StudentAssistant rdfs:subClassOf uib:Teacher .

?

Complement classes

- A complement class contains all the individuals *that are not* in another class:
  - uib:ExternalCensor owl:complementOf uib:InternalCensor .

Complement classes

- A complement class contains all the individuals *that are not* in another class:
  - uib:ExternalCensor owl:complementOf uib:InternalCensor .
  - *...but is this correct?!*

Complement classes

- A complement class contains all the individuals *that are not* in another class:
  - uib:ExternalCensor
    a owl:Class;
    owl:complementOf uib:InternalCensor .

Complement classes

- A complement class contains all the individuals *that are not* in another class:
  - uib:ExternalCensor

```
        owl:intersectionOf (
                uib:Censor
                owl:complementOf uib:InternalCensor
        ) .
```

Complement classes

- A complement class contains all the individuals *that are not* in another class:
  - uib:ExternalCensor

```
        owl:intersectionOf (
                uib:Censor
                [     a owl:Class ;
                      owl:complementOf uib:InternalCensor
                ]
        ) .
```

Complement classes

- A complement class contains all the individuals *that are not* in another class:
  - uib:ExternalCensor

```
uib:ExternalCensor
        owl:intersectionOf (
                uib:Censor
                [  owl:complementOf uib:InternalCensor  ]
        ) .
```

Closed World Assumption (CWA)

- Whenever something is not explicitly stated in the ontology, can we assume that the opposite is the case?
  - DBpedia only lists three James Dean movies – can we thus assume that he only played in three?
- Classical logic and many ICT languages assume so:
  - this is the *"Closed World Assumption" (CWA)*
- *In RDF and OWL, we do not assume that something is false just because it is not stated*
  - this is the *"Open World Assumption" (OWA)*

Enumeration classes

- An *enumeration class* is defined by exhaustively listing all its member individuals, e.g.:
  - [a owl:Class ;
    owl:oneOf (cal:Spring ... cal:Winter)] .
- An enumeration class is *closed*
  - there are no other member individuals
  - ensured by using *RDF Collections:*
    - rdf:List, rdf:first, rdf:rest, rdf:nil
- Does *not* imply that the individuals are distinct
  - this must be stated explicitly

Other ways to write complex classes

- Why can also write:

```
cal:Season
    owl:oneOf ( cal:Spring ... cal:Winter ) .
```

  or

```
cal:Season owl:equivalentClass [
    owl:oneOf ( cal:Spring ... cal:Winter ) ] .
```

- or (a weaker claim):

```
cal:Season owl:subClassOf [
    owl:oneOf ( cal:Spring ... cal:Winter ) ] .
```

- Reason:
  - *rdfs:subClassOf* can be computationally more efficient
  - *owl:equivalentClass* is sometimes implemented as a costly two-way *rdfs:subClassOf*

Summary: complex classes

- owl:oneOf
- owl:unionOf
- owl:intersectionOf
- owl:complementOf (and the *CWA*)
- owl:NegativePropertyAssertion, owl:sourceIndividual, owl:assertionProperty, owl:targetIndividual

OWL restriction classes

Property value restrictions

- Defining a class by a particular value on one of its properties, e.g.:
  - ex:Republican

```
a owl:Restriction ;
owl:onProperty dbo:hasParty ;
owl:hasValue dbr:Republican_Party_(United_States) .
```

Property value restrictions

- Defining a class by a particular value on one of its properties, e.g.:
  - ex:Republican owl:intersectionOf (

```
ex:Republican owl:intersectionOf (
        dbr:Person
        [    a owl:Restriction ;
             owl:onProperty dbo:hasParty ;
             owl:hasValue dbr:Republican_Party_(United_States)
        ]
) .
```

Existential property restrictions

- Defining a class by the existence of a relation (object property) to an individual in (another or the same) class, e.g.:
  - ex:President owl:intersectionOf (

```
        dbr:Person
        [     a owl:Restriction ;
              owl:onProperty ex:presidentOf ;
              owl:someValuesFrom owl:Thing
        ]
) .
```

- *owl:someValuesFrom:* each individual in the defined class has *at least one* object property (given by owl:onProperty) to an individual in the other class (given by owl:someValuesFrom)

Existential property restrictions

- Defining a class by the existence of a relation (object property) to an individual in (another or the same) class, e.g.:
  - dbr:President_(government_title) owl:intersectionOf (

```
          dbr:Person
          [    a owl:Restriction ;
               owl:onProperty ex:presidentOf ;
               owl:someValuesFrom dbr:Nation
          ]
      ) .
```

- *owl:someValuesFrom:* each individual in the defined class has *at least one* object property (given by owl:onProperty) to an individual in the other class (given by owl:someValuesFrom)

Existential property restrictions

- Defining a class by the existence of a relation (object property) to an individual in (another or the same) class, e.g.:
  - ex:BipartisanCommittee owl:intersectionOf (

```
        foaf:Group
        [     a owl:Restriction ;
              owl:onProperty foaf:member ;
              owl:someValuesFrom ex:Republican_(United_States)
        ]
        [     a owl:Restriction ;
              owl:onProperty foaf:member ;
              owl:someValuesFrom ex:Democrat_(United_States)
        ]
) .
```

Universal property restrictions

- Defining a class by the necessity of a relation (object property) only to individuals in (another or the same) class, e.g.:
  - ex:RepublicanCommittee owl:intersectionOf (

```
        foaf:Group
        [   a owl:Restriction ;
            owl:onProperty foaf:member ;
            owl:allValuesFrom ex:Republican_(United_States)
        ]
) .
```

Universal property restrictions

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            owl:allValuesFrom ex:Republican_(United_States)
        ]
) .
```

What is wrong here?

Universal property restrictions

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```
        foaf:Group
        [   a owl:Restriction ;
            owl:onProperty foaf:member ;
            owl:allValuesFrom ex:Republican_(United_States)
        ]
        [   a owl:Restriction ;
            owl:onProperty foaf:member ;
            owl:someValuesFrom owl:Thing
        ]
    ) .
```

Universal property restrictions

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  - ex:RepublicanCommittee owl:intersectionOf (

```
        foaf:Group
        [    a owl:Restriction ;
             owl:onProperty foaf:member ;
             owl:allValuesFrom [
                  a owl:Restriction ;
                  owl:onProperty ex:hasParty ;
                  owl:hasValue ex:Republican_Party_(United_States)
             ] ]
        [    a owl:Restriction ;
             owl:onProperty foaf:member ;
             owl:someValuesFrom owl:Thing
        ] ) .
```

Property self-reflexion

- Defining a class by a *Self* value on one of its properties, e.g.:
  - ex:Narcissist

```
a                owl:Restriction ;
owl:onProperty   ex:loves ;
owl:hasSelf      "true"^^xsd:boolean .
```

Datatype property restriction

- Restrictions on data range, e.g.:
  - fam:personAge rdfs:range

```
[    a rdfs:Datatype;
     owl:onDatatype  xsd:integer;
     owl:withRestrictions (
         [ xsd:minInclusive  "0"^^xsd:integer ]
         [ xsd:maxInclusive  "130"^^xsd:integer ]  )
] .
```

  - :toddlerAge rdfs:range

```
[    a rdfs:Datatype;
     owl:oneOf ( "1"^^xsd:integer  "2"^^xsd:integer)
] .
```

Cardinality restriction

- Defining a class by the number of object values its individuals have for some property, e.g.:
  - music:Quartet owl:intersectionOf (

```
music:Quartet owl:intersectionOf (
        music:Ensemble
        [   a owl:Restriction ;
            owl:onProperty music:hasMusician ;
            owl:cardinality 4    ]
) .
```

- owl:cardinality gives the *exact cardinality*
  owl:minCardinality gives the *least cardinality*
  owl:maxCardinality gives the *greatest cardinality*

Qualified cardinality restriction

- Defining a class by the number of object values its individuals have *of a given class* for some property, e.g.:
  - pol:Triumvirate owl:intersectionOf (
    pol:PoliticalLeadership
    [a owl:Restriction ;
    owl:onProperty pol:hasMember ;
    owl:qualifiedCardinality 3 ;
    owl:onClass pol:PoliticalLeader]
) .
- owl:qualifiedCardinality gives the *exact cardinality*
  owl:minQualifiedCardinality gives the *least cardinality*
  owl:maxQualifiedCardinality gives the *greatest cardinality*

Qualified cardinality restriction

- music:StringQuartet owl:intersectionOf (

```
music:MusicalQuartet
[     a owl:Class ;
      owl:onProperty music:hasMusician ;
      owl:qualifiedCardinality “2” ;
      owl:onClass music:Violinist ]
[     a owl:Class ;
      owl:onProperty music:hasMusician ;
      owl:qualifiedCardinality “1” ;
      owl:onClass music:Violist    ]
[     a owl:Class ;
      owl:onProperty music:hasMusician ;
      owl:qualifiedCardinality “1” ;
      owl:onClass music:Cellist    ] ) .
```

Summary: property restrictions

- owl:Restriction owl:onProperty
- owl:someValuesFrom, owl:allValuesFrom, owl:hasValue
- owl:cardinality, owl:minCardinality, owl:maxCardinality
- owl:qualifiedCardinality, owl:minQualifiedCardinality, owl:maxQualifiedCardinality, owl:onClass

Next week:
Vocabularies