Knowledge Graphs
Web Ontology Language (OWL)

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Previously on “Knowledge Graphs”

- Back to the lecture on RDF Schema
- We have the following statement:
  - "Madrid is the capital of Spain."

- We can get the following information:
  - "Madrid is the capital of Spain." ✔
  - "Spain is a state." ✔
  - "Madrid is a city." ✔
  - "Madrid is located in Spain." ✔
  - "Barcelona is not the capital of Spain." ✖
  - "Madrid is not the capital of France." ✖
  - "Madrid is not a state." ✖
  - ...

Previously on “Knowledge Graphs”

- What we cannot express (up to now):
  - "Every state has *exactly one* capital"
    - Property cardinalities
  - "Every city can only be the capital of one state."
    - Functional properties
  - "A city cannot be a state at the same time."
    - Class disjointness
  - ...

- For those, we need more expressive languages than RDFS!

Previously on “Knowledge Graphs”

- We have learned about ontologies
  – and RDF Schema as a language for building simple ontologies

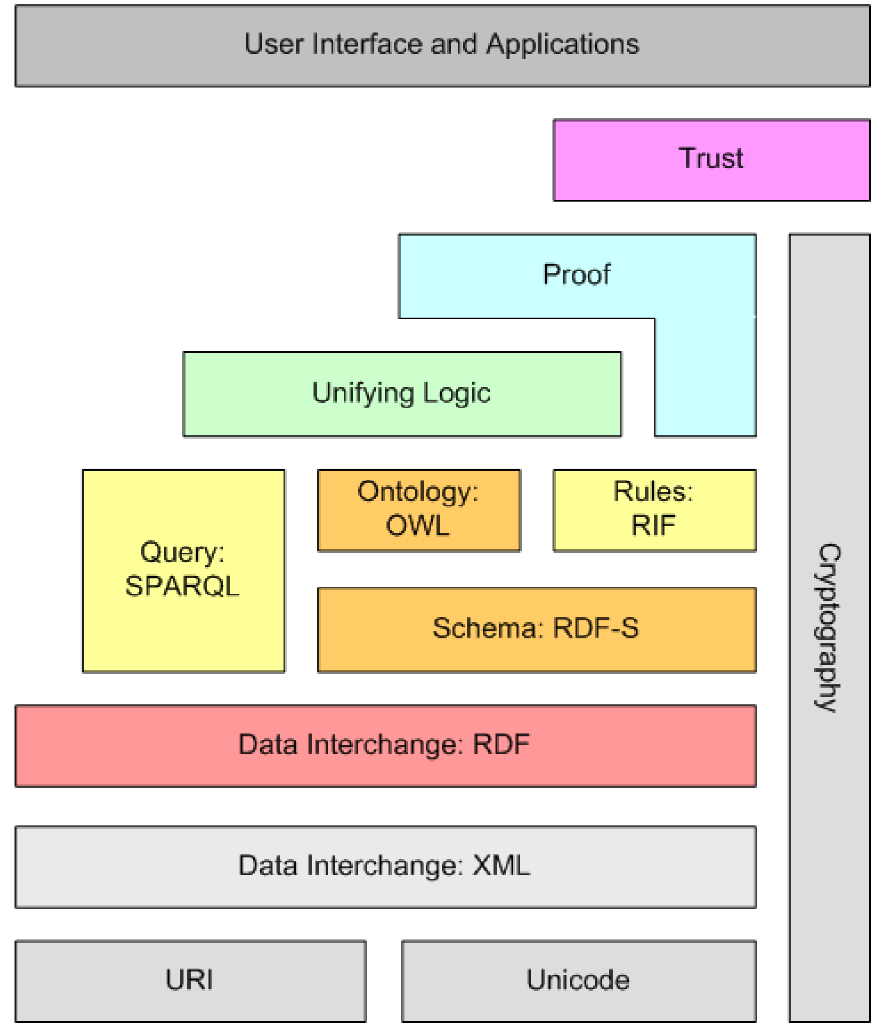
- With RDF Schema, we can express some knowledge about a domain
  – but not everything, e.g., cardinalities
  – we cannot produce contradictions
  – we cannot circumvent the Non Unique Naming Assumption
  – we cannot circumvent the Open World Assumption
  – ...

Semantic Web Technology Stack

here be dragons...

Knowledge Graph
Technologies
(This lecture)

Technical
Foundations



Berners-Lee (2009): *Semantic Web and Linked Data*
http://www.w3.org/2009/Talks/0120-campus-party-tbl/

Web Ontology Language (OWL)

- Hey, wait...

Web Ontology Language (OWL)

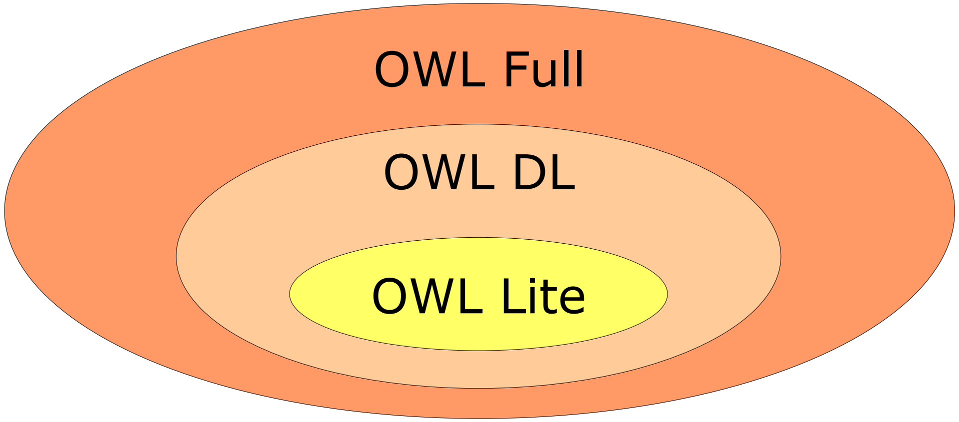
- More powerful than RDF Schema
- W3C Standard (2004), OWL2 (2009)

- Trade-off:
  - Expressive power
  - Complexity of reasoning
  - Decidability

- Solution: different variants of OWL, e.g.,
  - OWL Lite, OWL DL, OWL Full
  - Profiles in OWL2

Web Ontology Language (OWL)

- Three variants
  - increasing expressive power
  - backwards compatible
    - each OWL Lite ontology is valid in OWL DL and OWL Full
    - each OWL DL ontology is valid in OWL Full



OWL and RDF Schema

- both are based on RDF
  - OWL ontologies can also be expressed in RDF
  - as triples or in XML notation

- Compatibility
  - OWL Lite and OWL DL are not fully compatible to RDF Schema
    - but reuse some parts of RDF Schema
  - OWL Full and RDF Schema are fully compatible

OWL: Classes

- Basic concept (`owl:Class`)

- Subclasses as we know them from RDFS: `rdfs:subClassOf`
  - In particular, the following holds:
    `owl:Class rdfs:subClassOf rdfs:Class .`

- Two predefined classes:
  - `owl:Thing`
  - `owl:Nothing`

- For each class `c`, the following axioms hold:
  - `c rdfs:subClassOf owl:Thing .`
  - `owl:Nothing rdfs:subClassOf c .`

OWL: Classes

- Classes can be intersections of others:

```
:SwimmingMammals owl:intersectionOf
  (:SwimmingAnimals :Mammals) .
```

- There are also set unions and set differences
  - but not in OWL Lite

OWL: Properties

- RDF Schema does not distinguish literal and object valued properties:

```
:name a rdf:Property .
:name rdfs:range xsd:string .

:knows a rdf:Property .
:knows rdfs:range foaf:Person .
```

- Without specifying the range, “dual use” of an RDF property is not forbidden:

```
:peter :knows :john .
:peter :knows "mary"^^xsd:string .
```

OWL: Properties

- RDF Schema does not distinguish literal and object valued properties:

```
:name a rdf:Property .
:name rdfs:range xsd:string .

:knows a rdf:Property .
:knows rdfs:range foaf:Person .
```

- In contrast, OWL distinguishes
  - `owl:DatatypeProperty`
  - `owl:ObjectProperty`
- The following axioms hold:
  - `owl:DatatypeProperty rdfs:subClassOf rdf:Property .`
  - `owl:ObjectProperty rdfs:subClassOf rdf:Property .`

OWL: Properties

- As in RDF Schema, there can be hierarchies and domains/ranges:

```
:capitalOf rdfs:subPropertyOf :locatedIn .
```

- Domain
  - only classes for OWL Lite, classes or restrictions* for OWL DL/Full

```
:name rdfs:domain foaf:Person .
```

- Range
  - XML Datatypes for `owl:DatatypeProperty`

```
:name rdfs:range xsd:string .
```

  - Classes or restrictions* for `owl:ObjectProperty`

```
:knows rdfs:range foaf:Person .
```

* we'll get there soon

Equality and Inequality (1)

- Equality between individuals
  - Allows using multiple definitions/descriptions of an entity
  - in other datasets as well
  - solves some problems of the Non unique naming assumption

```
:Muenchen owl:sameAs :Munich .
```

- We have seen this used for Linked Open Data
  - as a means to establish links between datasets

```
myDataset:Mannheim owl:sameAs dbpedia:Mannheim .
```

Equality and Inequality (2)

- Equality between classes and properties
  - allows for relations between datasets on the schema level
  - gives way to more complex constructs

```
:UniversityTeachers owl:equivalentClass :Lecturers .
:teaches owl:equivalentProperty :lecturerFor .
```

- Also useful for Linked Open Data:

```
my:createdBy owl:equivalentProperty foaf:maker .
```

Equality and Inequality (3)

- Inequality between individuals
  - Allows some useful reasoning
  - as we will see soon

```
:Munich owl:differentFrom :Hamburg .
```

- Shorthand notation for multiple entities:

```
owl:AllDifferent owl:distinctMembers
  (:Munich :Hamburg :Berlin :Darmstadt :Mannheim) .
```

Why can't we Simply Use only owl:sameAs?

- In OWL (Lite+DL), we must not mix classes, properties, and instances

- `owl:sameAs` has `owl:Thing` as domain/range
- `owl:equivalentClass` has `rdfs:Class` as domain/range
  - recap: `owl:Class rdfs:subClassOf rdfs:Class`
- `owl:equivalentProperty` has `rdf:Property` as domain/range
  - `owl:ObjectProperty rdfs:subClassOf rdf:Property`
  - `owl:DatatypeProperty rdfs:subClassOf rdf:Property`

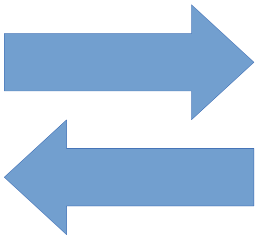
Special Properties in OWL

- Symmetric Properties

```
:sitsOppositeOf a owl:SymmetricProperty .
 :Tom :sitsOppositeOf :Sarah .
→:Sarah :sitsOppositeOf :Tom .
```

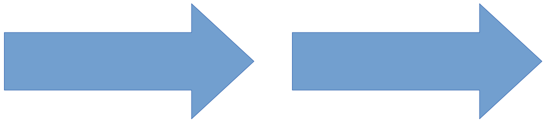
- Inverse Properties

```
:supervises owl:inverseOf :supervisedBy .
 :Tom :supervises :Julia .
→:Julia :supervisedBy :Tom .
```



- Transitive Properties

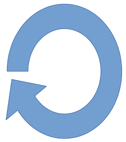
```
:hasOfficeMate a owl:TransitiveProperty .
 :Tom :hasOfficeMate :Jon . :Jon :hasOfficeMate :Kim .
→:Tom :hasOfficeMate :Kim .
```



Special Properties introduced with OWL2

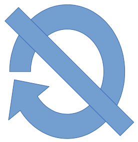
- Reflexive, irreflexive, and asymmetric properties
- Everybody is a relative of him/herself

```
:relativeOf a owl:ReflexiveProperty .
```



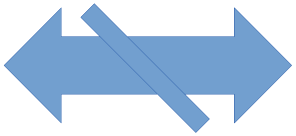
- Nobody can be his/her own parent

```
:parentOf a owl:IrreflexiveProperty .
```



- If I am taller than you, you cannot be taller than me

```
:tallerThan a owl:AsymmetricProperty .
```



Restrictions on Property Types

- Only ObjectProperties may be transitive, symmetric, inverse, and reflexive
  - DataProperties may not be
- Why?
- *Previously on RDF:*
  - "Literals can only be objects, never subjects or predicates."

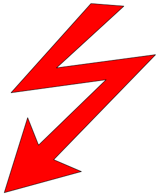
Restrictions on Property Types

- Assuming that

```
:samePerson a owl:DatatypeProperty .
:samePerson rdfs:range xsd:string .
:samePerson a owl:SymmetricProperty .

:Peter :samePerson "Peter" .

→"Peter" :samePerson :Peter .
```



Restrictions on Property Types

- Assuming that

```
:hasName a owl:DatatypeProperty .
:hasName rdfs:range xsd:string .
:hasName owl:inverseOf :nameOf .

:Peter :hasName "Peter" .

→"Peter" :nameOf :Peter .
```

Restrictions on Property Types

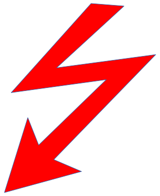
- `owl:TransitiveProperty` is also restricted to ObjectProperties

```
:hasPseudonym a owl:DatatypeProperty .
:hasPseudonym rdfs:range xsd:string .
:hasPseudonym a owl:TransitiveProperty .

:Thomas :hasPseudonym "Dr. Evil" .

+ "Dr. Evil" :hasPseudonym "Skullhead" .

→:Thomas :hasPseudonym "Skullhead" .
```



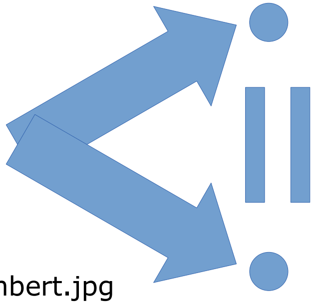
- Which statement would we need here to make the conclusion via the `owl:TransitiveProperty`?

Functional Properties

- Usage

```
:hasCapital a owl:FunctionalProperty
:Finland :hasCapital :Helsinki .
:Finland :hasCapital :Helsingfors .
→:Helsinki owl:sameAs :Helsingfors .
```

- Interpretation
  - if A and B are related via fp
  - and A and C are related via fp
  - then, B and C are equal
- simply speaking: fp(x) is unique for each x
- “there can only be one”



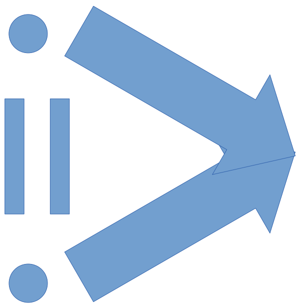
http://www.allmystery.de/dateien/uh60808,1274716100,highlander-christopher-lambert.jpg

Inverse Functional Properties

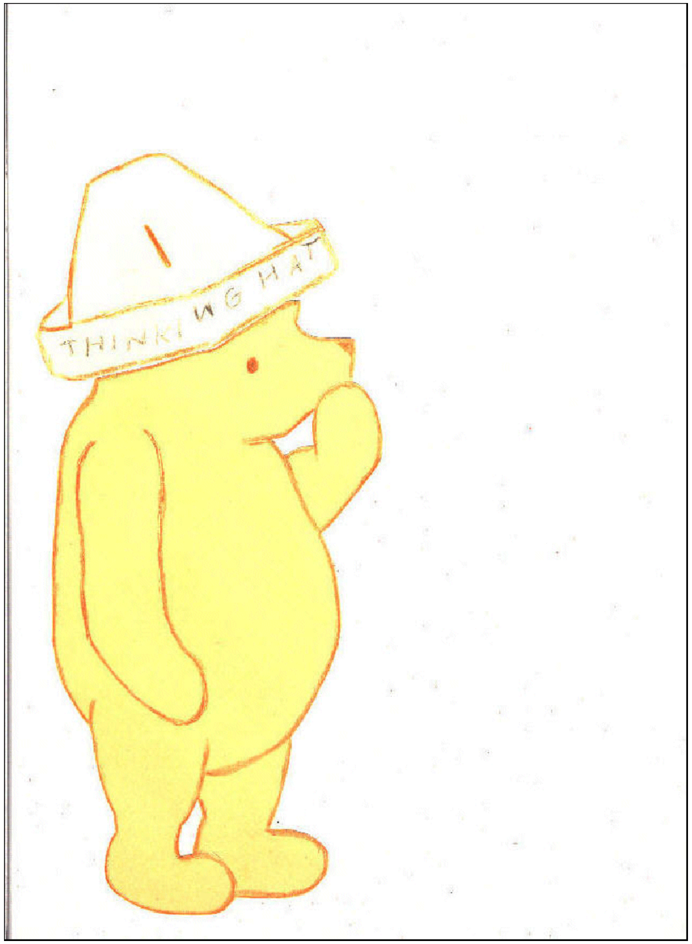
- Usage

```
:capitalOf a owl:InverseFunctionalProperty .
:Helsinki :capitalOf :Finland .
:Helsingfors :capitalOf :Finland .
→:Helsinki owl:sameAs :Helsingfors .
```

- Interpretation
  - if A and C are in relation ifp
  - and B and C are in relation ifp
  - then, A and B are the same
- Simply speaking: ifp(x) is a unique identifier for x
  - like a primary key in a database



Pooh!



- OWL is, in fact, more powerful
- ...but we can achieve lots with what we already learned
- Let's get back to the example...

Previously on “Knowledge Graphs”

- Let's look at that sentence:
  - "Madrid is the capital of Spain."

- We can get the following information:
  - "Madrid is the capital of Spain." ✔
  - "Spain is a state." ✔
  - "Madrid is a city." ✔
  - "Madrid is located in Spain." ✔
  - "Barcelona is not the capital of Spain." ✖
  - "Madrid is not the capital of France." ✖
  - "Madrid is not a state." ✖
  - ...

Expressive Ontologies using OWL

- "Barcelona is not the capital of Spain." ✖
- Why not?
  - Countries have exactly one capital
  - Barcelona and Madrid are not the same

- In OWL:

```
:capitalOf a owl:InverseFunctionalProperty .
:Madrid :capitalOf :Spain .
:Madrid owl:differentFrom :Barcelona .

ASK { :Barcelona :capitalOf :Spain . } → false
```

Expressive Ontologies using OWL

- "Madrid is not the capital of France." ✖
- Why not?
  - A city can only be the capital of one country
  - Spain and France are not the same
- Also:

```
:capitalOf a owl:FunctionalProperty .
:Madrid :capitalOf :Spain .
:Spain owl:differentFrom :France .

ASK { :Madrid :capitalOf :France . } → false
```

Restrictions

- Define characteristics of a class
  - A powerful and important concept in OWL
  - Example: Vegan recipes only contain vegetables as ingredients

```
:VeganRecipe rdfs:subClassOf :Recipe .
:VeganRecipe rdfs:subClassOf [
 a owl:Restriction ;
 owl:onProperty :hasIngredient ;
 owl:allValuesFrom :Vegetable .
] .
```

Further Examples for Restrictions

- Every human as exactly one mother

```
:Human rdfs:subClassOf [
 a owl:Restriction ;
 owl:onProperty :hasMother ;
 owl:cardinality 1^^xsd:integer .
] .
```

- Standard bicycles are vehicles without a motor

```
:StandardBicycle rdfs:subClassOf :Vehicle .
:StandardBicycle rdfs:subClassOf [
 a owl:Restriction ;
 owl:onProperty :hasMotor ;
 owl:cardinality 0^^xsd:integer .
] .
```

Restrictions vs. Ranges

- Restrictions are local to a class

```
:VeganRecipe rdfs:subClassOf [
 a owl:Restriction ;
 owl:onProperty :hasIngredient ;
 owl:allValuesFrom :Vegetable .
] .
```

  – other classes may use `hasIngredient` with meat or fish

- Range: a global restriction

```
:hasIngredient rdfs:range :Food .
```

  – this holds *once and for all* whenever `hasIngredient` is used

The Anatomy of a Restriction

- onProperty
  - defines the property on which the restriction should hold
- Restriction of values
  - owl:allValuesFrom – all values must be in this class
  - owl:someValuesFrom – at least one value must be in this class
- Restriction of cardinalities
  - owl:minCardinality – at least n values
  - owl:maxCardinality – at most n values
  - owl:cardinality – exactly n values
- Both cannot be combined

OWL Lite: only n=0 or n=1

Further Examples for Restrictions

- All ball sports require a ball

```
:BallSports rdfs:subClassOf [
  a owl:Restriction ;
  owl:onProperty :requires ;
  owl:someValuesFrom :Ball .
] .
```

- All sports for which a ball is required are ball sports

```
:BallSports owl:equivalentClass [
  a owl:Restriction ;
  owl:onProperty :requires ;
  owl:someValuesFrom :Ball .
] .
```

- Where is the difference?

Further Examples for Restrictions

- Given:

```
:BallSports owl:equivalentClass [
 a owl:Restriction ;
 owl:onProperty :requires ;
 owl:someValuesFrom :Ball .
] .

:Soccer :requires :soccerBall .
:soccerBall a :Ball.
```

- A reasoner may conclude that soccer is a ball sports
- This would not work with subClassOf
- Caveat: gymnastics with a ball are also recognized as ball sports...

Qualified Restrictions in OWL2

- In OWL, cardinalities and value restrictions may not be combined
- i.e., use either all/someValuesFrom or min/maxCardinality
- OWL 2 introduces *qualified restrictions*

- Example: a literate person has to have read at least 1,000 books (newspapers and magazines do not count!)

```
:LiteratePerson rdfs:subClassOf [
    a owl:Restriction ;
    owl:onProperty :hasRead;
    owl:minQualifiedCardinality "1000"^^xsd:integer ;
    owl:onClass :Book . ] .
```

Analogously, there are also `owl:maxQualifiedCardinality` and `owl:qualifiedCardinality`

Using Restriction Classes as Ranges

- Restrictions can also be used in other contexts
- Example: books, newspapers, and posters can be read
  - essentially: everything that contains letters

- Range of the predicate *reads*:

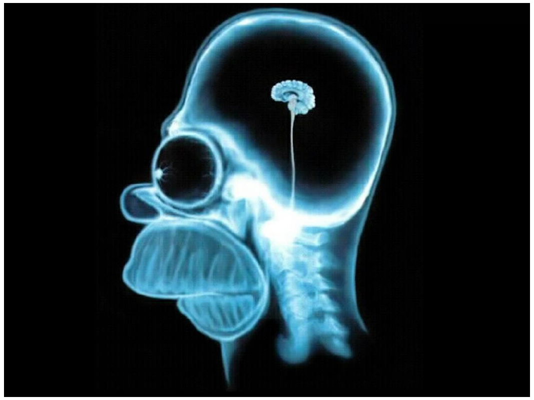
```
:reads rdfs:range [
 a owl:Restriction ;
 owl:onProperty :containsLetter ;
 owl:minCardinality 1^^xsd:integer .
] .
```

Using Restrictions as Domains

- If it works for ranges, it also works for domains
- e.g.: to think about something, a brain is required

- Domain of the *thinksAbout* property:

```
:thinksAbout rdfs:domain [
 a owl:Restriction ;
 owl:onProperty :hasBodyPart ;
 owl:someValuesFrom :Brain .
] .
```



- Note: only in OWL DL/Full

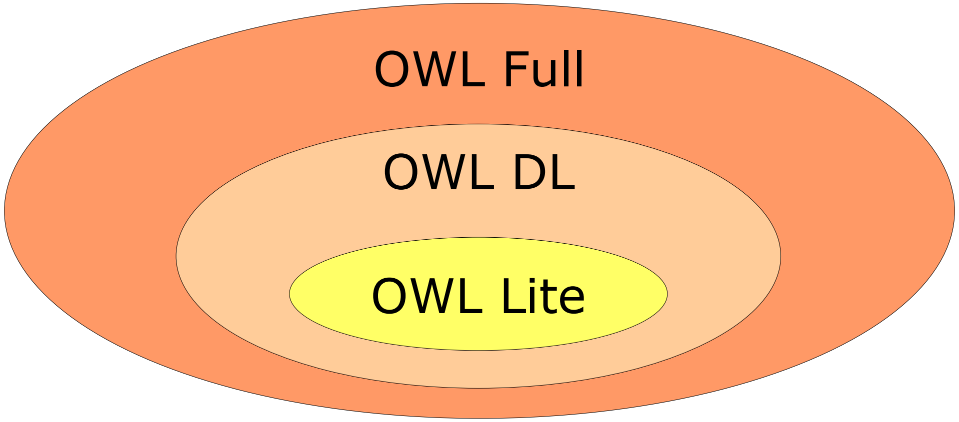
Nesting Restrictions

- It is always possible to make things more complex
- e.g.: grandparents have children who themselves have at least one child

```
:GrandParent owl:equivalentClass [
 a owl:Restriction ;
 owl:onProperty :hasChild ;
 owl:someValuesFrom [
        a owl:Restriction ;
        owl:onProperty :hasChild ;
        owl:minCardinality 1^^xsd:integer .
 ] .
] .
```

Web Ontology Language (OWL)

- What we have seen up to now
  - the vocabulary of OWL Lite
  - useful in many cases
  - "A little semantics goes a long way."
- OWL DL and OWL Full are more powerful
  - but also harder to handle



OWL DL

- DL stands for "Description Logics"
  - a subset of first order logics
  - we will get back to that in the next lecture
- OWL DL introduces
  - the full set of cardinality restrictions (OWL Lite allows only 0 and 1)
  - more set operators
  - closed classes
  - value based restrictions
  - restrictions on datatypes
  - ...

Complex Set Definitions

- Set union

```
:FacultyMembers owl:unionOf
  (:Students, :Professors) .
```

- Complement set

```
:LivingThings owl:complementOf :InanimateThings .
```

- Disjoint sets

```
:EdibleMushrooms owl:disjointWith
  :PoisonousMushrooms .
```

Previously on “Semantic Web Technologies”

- Let's look at that sentence:
  - "Madrid is the capital of Spain."

- We can get the following information:
  - "Madrid is the capital of Spain." ✔
  - "Spain is a state." ✔
  - "Madrid is a city." ✔
  - "Madrid is located in Spain." ✔
  - "Barcelona is not the capital of Spain." ✔
  - "Madrid is not the capital of France." ✔
  - "Madrid is not a state." ✖
  - ...

Previously on “Semantic Web Technologies”

- "Madrid is not a state." ✖
- Why not?
  - Madrid is a city
  - Nothing can be a city and a state at the same time.
- In OWL:

```
:Madrid a :City .
:City owl:disjointWith :State .

ASK { :Madrid a :State . } → false
```

Complex Set Definitions

- We can combine class definitions and restrictions:

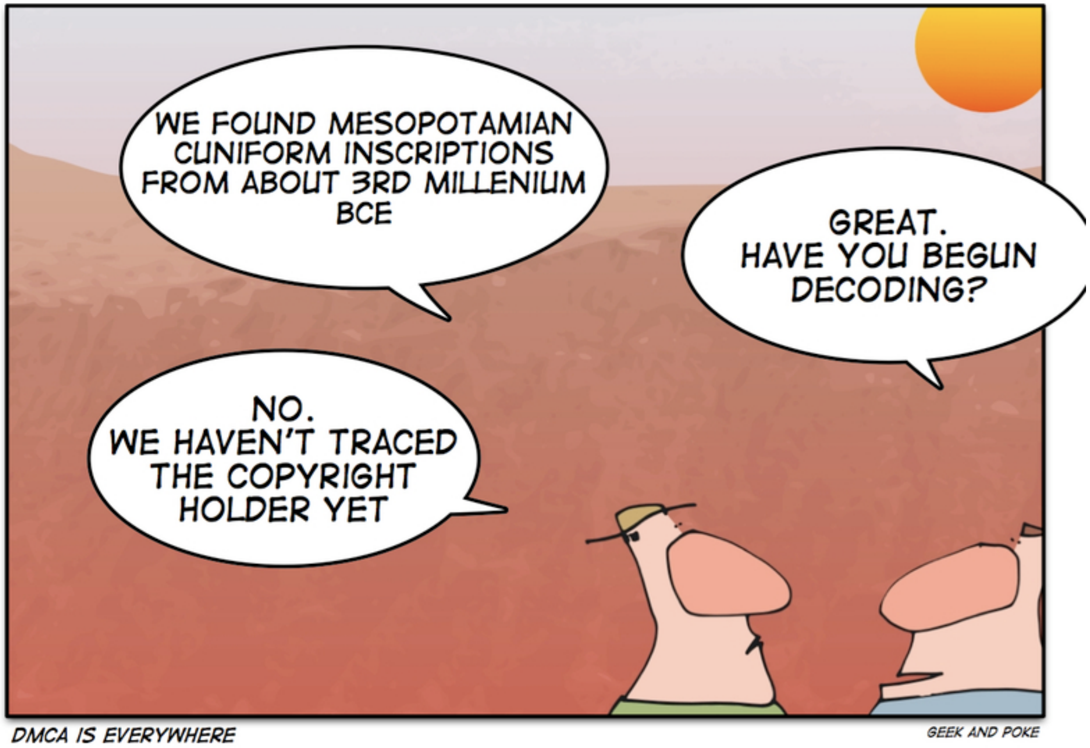
```
:VegetarianRecipe rdfs:subClassOf [
    a owl:Restriction ;
    owl:onProperty :hasIngredient ;
    owl:allValuesFrom [
          a owl:Class .
          owl:complementOf [
                owl:unionOf (:Meat :Fish)
          ]
    ]
] .
```

A Tale from the Road

- ALIS: EU funded research project (2006-2009)
- Automated Legal Intelligent System
  - automatic search for relevant European laws
  - given a legal case at hand
  - using ontologies, reasoning, etc.
  - use case: copyright law

A Tale from the Road

- One important differentiation (among others):
  - Single Author Work
  - Multi Author Work



http://geekandpoke.typepad.com/geekandpoke/2006/10/copyright_and_a.html

A Tale from the Road

- Naive Solution in OWL DL:

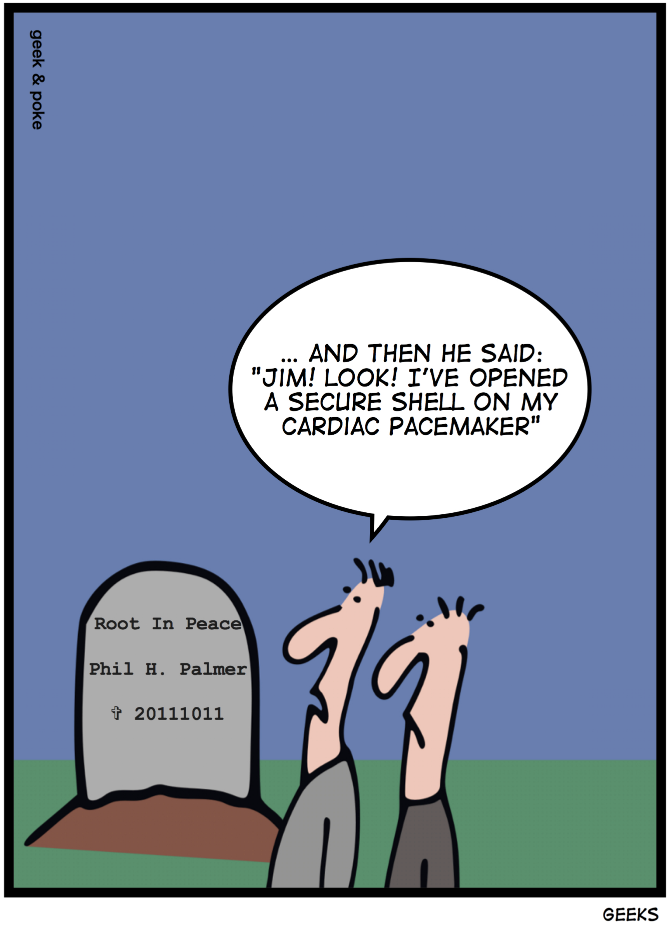
```
:hasAuthor a owl:ObjectProperty;
           rdfs:domain :Work ;
           rdfs:range :Author .

:SingleAuthorWork rdfs:subClassOf
   :Work,
   [ a owl:Restriction;
     owl:onProperty :hasAuthor ;
     owl:cardinality 1^^xsd:integer ] .

:MultiAuthorWork rdfs:subClassOf
   :Work,
   [ a owl:Restriction;
     owl:onProperty :hasAuthor ;
     owl:minCardinality 2^^xsd:integer ] .
```

A Tale from the Road

- Result:
  - not such a good idea
  - why not?



http://geekandpoke.typepad.com/geekandpoke/2006/10/copyright_and_a.html

A Tale from the Road

- Given

```
:DataMining :hasAuthor :IanWitten, :EibeFrank .
```

- what can we derive from that?

- OK, so we need

```
    :DataMining :hasAuthor :IanWitten, :EibeFrank .
    :IanWitten owl:differentFrom :EibeFrank .
→   :DataMining a :MultiAuthorWork .
```

A Tale from the Road

- Given:

```
:Faust :hasAuthor :Goethe .
```

- what can we derive from that?

- Since it worked for Multi Author Work, how about

```
:Work owl:disjointUnionOf
  (:SingleAuthorWork,:MultiAuthorWork) .
```

  ?

- Note: we can classify `:Faust` neither as Single nor as Multi Author Work

Recap: Principles of RDF

- Basic semantic principles of RDF:
  - AAA: Anybody can say Anything about Anything
- Non-unique name assumption
  - we can control it with owl:sameAs and owl:differentFrom
- Open World Assumption
  - so far, we have to live with it

Closed Classes

- The Open World Assumption says:
  - everything we do not know *could* be true

- Example:

```
:Tim a :PeopleInOfficeD219 .
:John a :PeopleInOfficeD219 .
:Mary a :PeopleInOfficeD219 .
```

- This does not mean that there cannot be more people in D219

```
:Mike a :PeopleInD219 .
```

- Sometimes, this is exactly what we want to say

Closed Classes

- Works with `owl:oneOf` in OWL DL
- Example:

```
:PeopleInOfficeD219 owl:oneOf (:Tim :John :Mary) .
```

- Now, what is the meaning of

```
:Mike a :PeopleInD219 .
```

?

Back to a Tale from the Road

- Solution:

```
:Faust a [ a owl:Restriction ;
           owl:onProperty :hasAuthor ;
           owl:allValuesFrom [
             a owl:Class ;
             owl:oneOf (:Goethe)
         ]
       ].
```

OWL DL: Restrictions with Single Values

- For ObjectProperties:

```
:AfricanStates owl:subClassOf [
   a owl:Restriction ;
   owl:onProperty :locatedOnContinent
   owl:hasValue :Africa ] .
```

- For DatatypeProperties:

```
:AlbumsFromTheEarly80s owl:subClassOf [
   a owl:Restriction ;
   owl:onProperty :year
   owl:dataRange
     (1980^^xsd:integer
      1981^^xsd:integer
      1982^^xsd:integer) ] .
```

OWL Lite/DL vs. OWL Full

- OWL Lite/DL: a resource is *either* an instance *or* a class *or* a property
- OWL Full does not have such restrictions:

```
:Elephant a owl:Class .
:Elephant a :Species .
:Elephant :livesIn :Africa .
:Species a owl:Class .
```

- OWL Lite/DL: classes are only instances of `owl:Class`
- OWL Lite/DL: classes and properties can only have a predefined set of relations (e.g., `rdfs:subClassOf`).

And Now for Something Completely Different

- Can we use OWL to solve a Sudoku?

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

Sudoku Solving in OWL

- What is our domain about?
- First of all, a closed class of numbers

```
:Number a owl:Class ;
  owl:oneOf (:1 :2 :3 :4 :5 :6 :7 :8 :9) .
  :1 owl:differentFrom (:2 :3 :4 :5 :6 :7 :8 :9) .
  :2 owl:differentFrom (:3 :4 :5 :6 :7 :8 :9) .
  ...
```

- ...and a lot of fields
  - that we want to fill with numbers
  - simplification: numbers are fields as well
  - we want to know which field equals which number

Sudoku Solving in OWL

- 81 Fields:

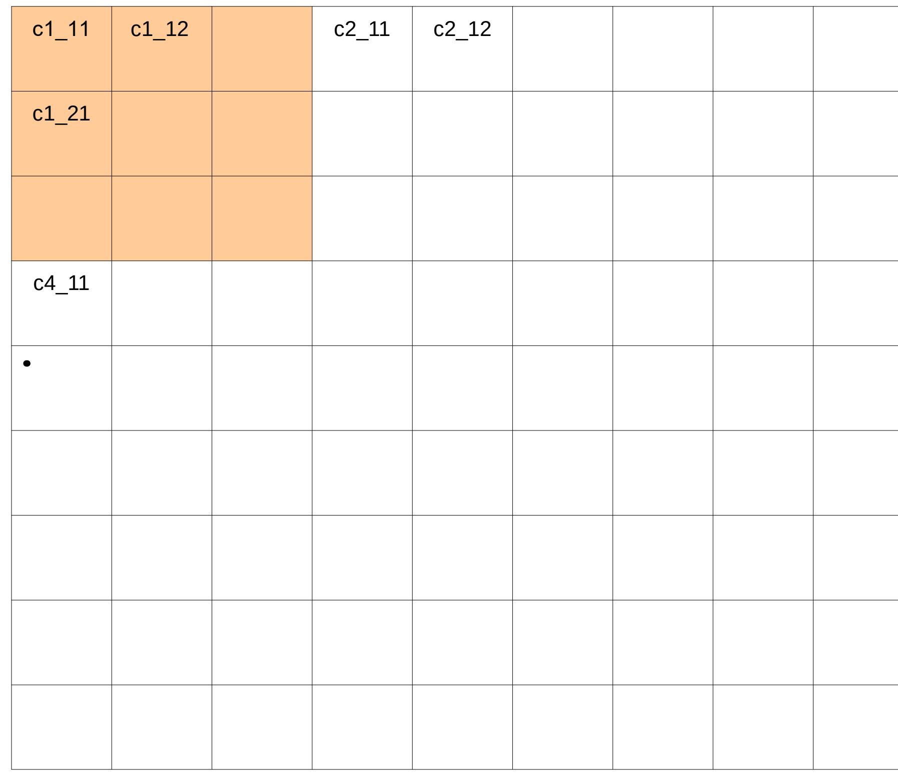
```
c1_11 a :Number .
c1_21 a :Number .
…
c1_33 a :Number .
c2_11 a :Number .
…
c9_33 a :Number .
```

c1_11	c1_12		c2_11	c2_12				
c1_21								
c4_11								

Sudoku Solving in OWL

- Fields in a quadrant are different

```
c1_11 owl:differentFrom
  c1_12, c1_13, …, c1_33 .
c1_12 owl:differentFrom
  c1_13, c1_21, …, c1_33
…
c1_32 owl:differentFrom
  c1_33 .
c2_11 owl:differentFrom
  c2_12, c2_13, …, c1_33 .
…
c9_32 owl:differentFrom
  c9_33 .
```



Sudoku Solving in OWL

- Fields in a row are different

```
c1_11 owl:differentFrom
  c1_12, c1_13, …, c3_13 .
…
```

c1_11	c1_12		c2_11	c2_12				
c1_21								
c4_11								

Sudoku Solving in OWL

- Fields in a column are different

```
c1_11 owl:differentFrom
  c1_21, c1_31, …, c3_31 .
```

…

c1_11	c1_12		c2_11	c2_12				
c1_21								
c4_11								

Sudoku Solving in OWL

- Last step: enter known numbers

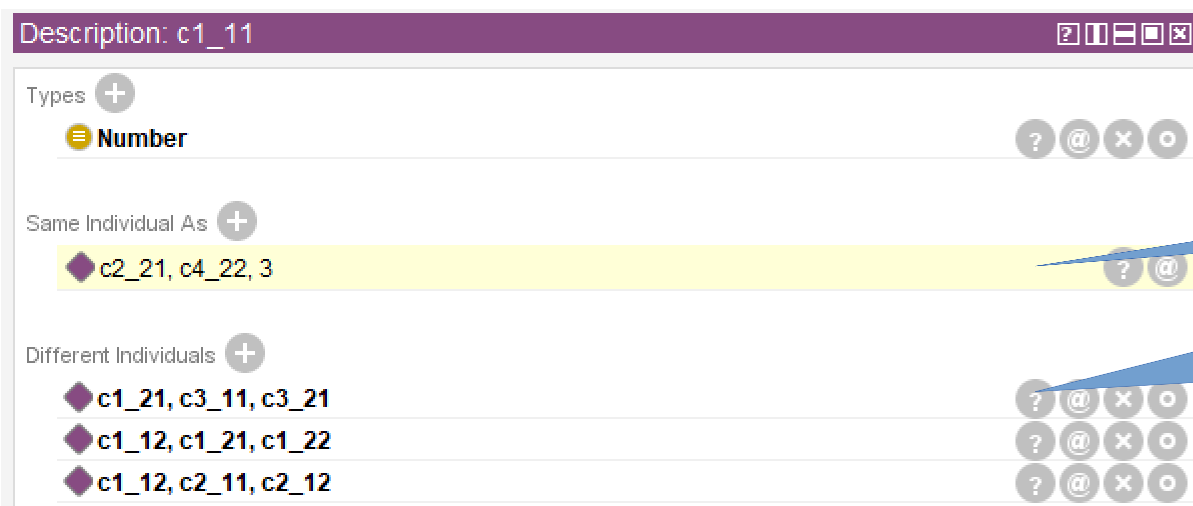
```
c1_11 owl:sameAs :5 .
c1_12 owl:sameAs :3 .
c1_21 owl:sameAs :6 .
…
```

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

Running this Example in Protégé

- We use a reasoner to infer implicit facts
- Here: number c1_11 (top left)

	4		
		3	
		2	
1			



Inferred: this is a 3

Defined conditions (horizontal, vertical, square)

Summary

- OWL allows defining more complex ontologies
- Flavors: OWL Lite, DL, Full
- Definitions of sets, restrictions, property characteristics
- In our example, we can now use the full set of conclusions:
  - "Barcelona is not the capital of Spain." ✔
  - "Madrid is not the capital of France." ✔
  - "Madrid is not a state." ✔

Coming Up Next

- Changes in OWL 2
- How does reasoning with OWL *actually* work?

Questions?