RDF Schema (RDFS)

IE650 Knowledge Graphs

Previously on “Knowledge Graphs”

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- Is RDF more powerful than XML?

- XML is a markup language
- for information
- In XML, arbitrary elements and attributes can be defined
- XML tag names are meaningless for a computer

- RDF is a markup language for information
- In RDF, arbitrary classes and predicates can be defined
- RDF class and predicate names are meaningless for a computer

Today: Schemas and Ontologies

- Last week's slides:

  - Node types ("classes") and edge types ("properties")
    - Are also referred to the "schema" of the graph (aka "ontology")
    - Can be defined with further restrictions
      - e.g., an edge of type "author" links a publication to a person

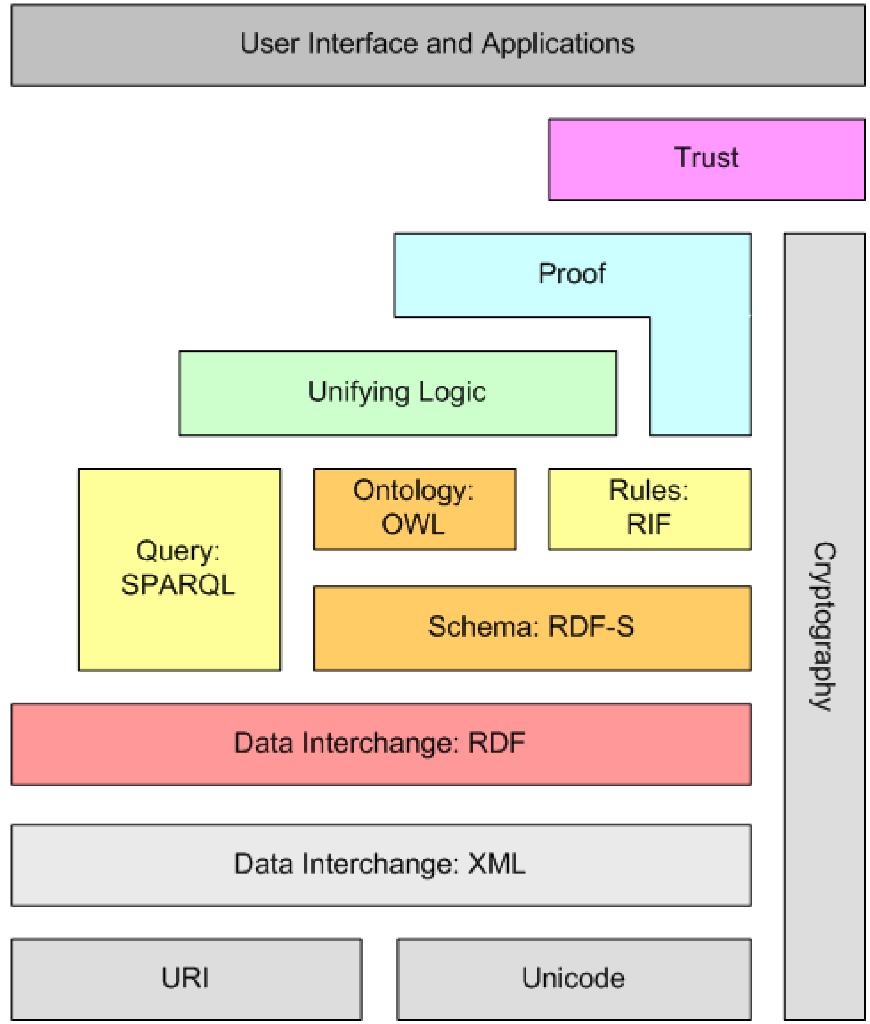
- Schemas and ontologies bring semantics to knowledge graphs
- Today:
  - Building simple ontologies with RDF Schema
  - Elements of RDF Schema
  - Automatic deduction with RDF Schema

The Semantic Web 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/

What is Missing up to Now?

- Basic premise: knowledge graphs should encode information so that humans and computers can understand it

- But what does understand actually mean?

„Madrid is the capital of Spain.“

Semantics

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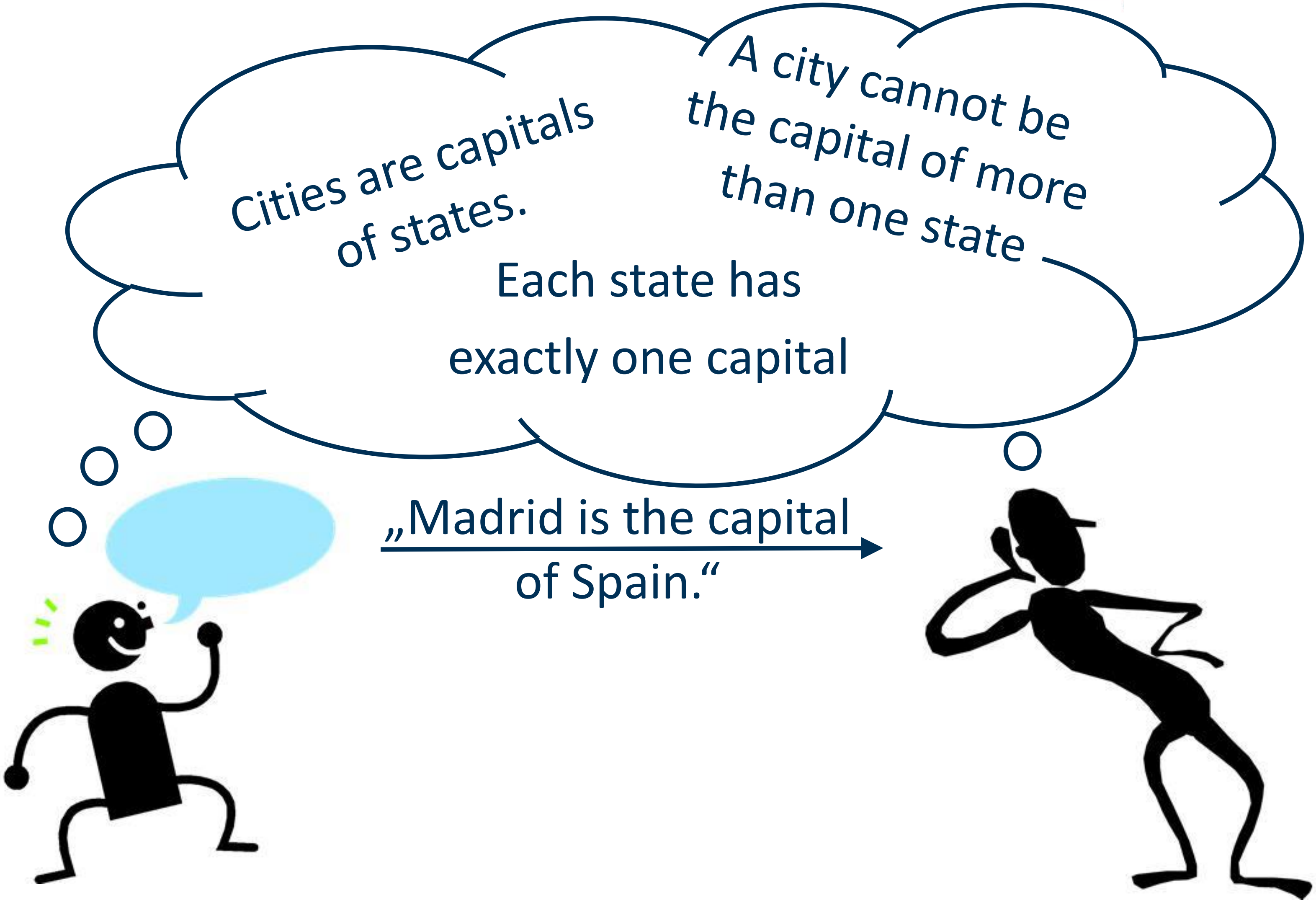
- Let's look at that sentence:
  - "Madrid is the capital of Spain."
- Published in a knowledge graph (i.e., using RDF):
  - :Madrid :capitalOf :Spain .
- How many pieces of information can we (i.e., humans) derive from that sentence?
  - (1 piece of information = 1 statement <S,P,O>)
  - Estimations? Opinions?

Semantics

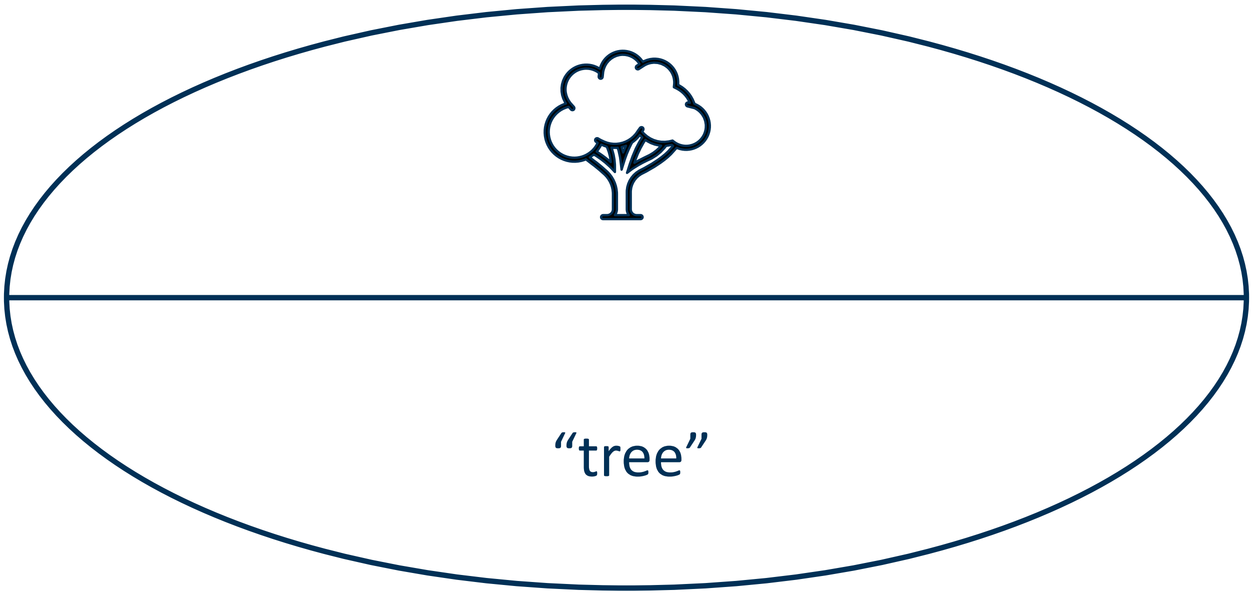
- Let's look at that sentence:
  - "Madrid is the capital of Spain."
- We can get the following information:
  - "Madrid is the capital of Spain."
  - "Spain is a state."
  - "Madrid is a city."
  - "Madrid is located in Spain."
  - "Barcelona is not the capital of Spain."
  - "Madrid is not the capital of France."
  - "Madrid is not a state."
  - ...

How do Semantics Work?



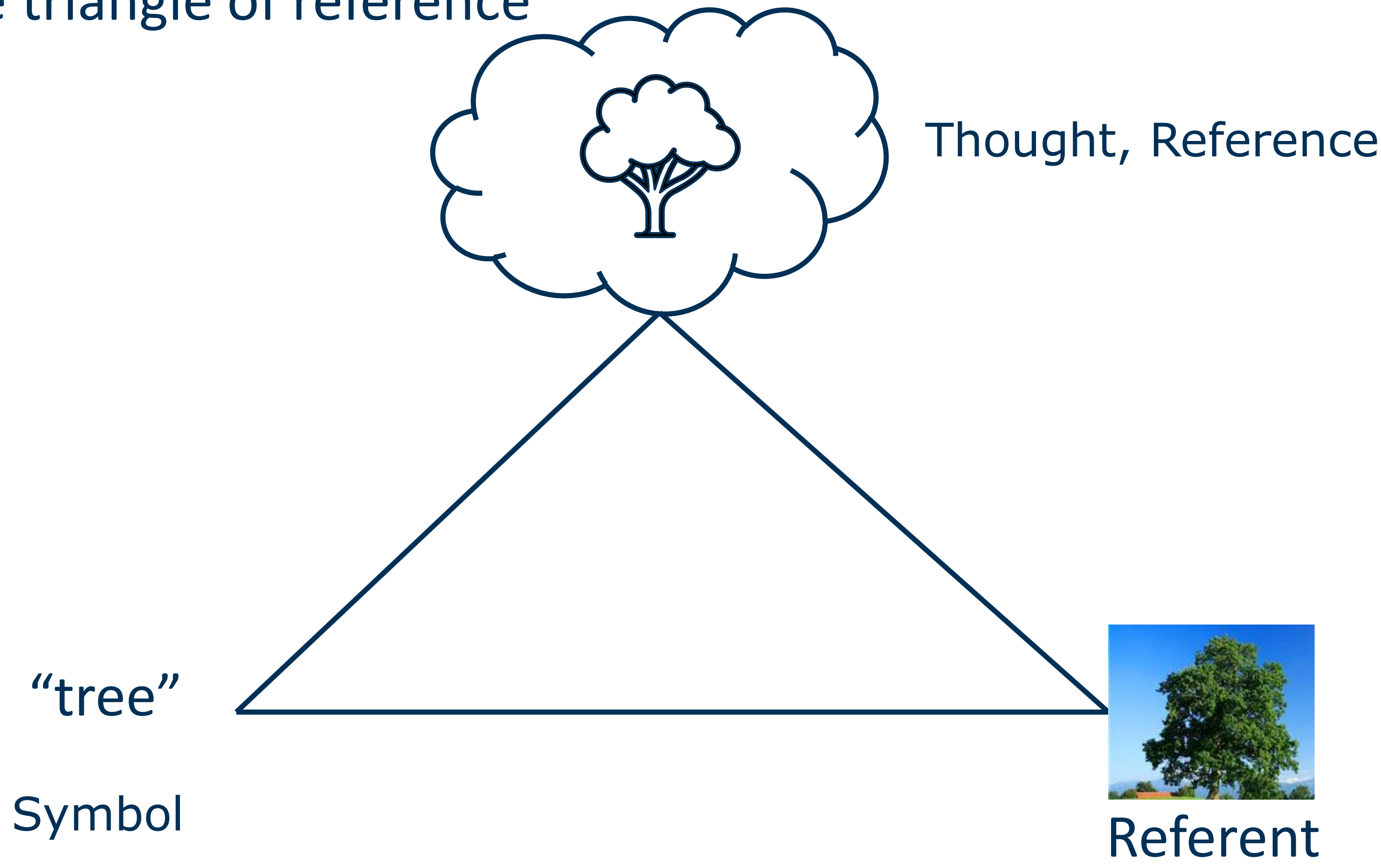
An Excursion to Linguistics

- Saussure's idea of a linguistic sign
- Ferdinand de Saussure (1857-1913):
  - Signifier (signifiant) and signified (signifié) cannot be separated from each other



An Excursion to Linguistics

- The triangle of reference



Charles Odgen (1923): The Meaning of Meaning.

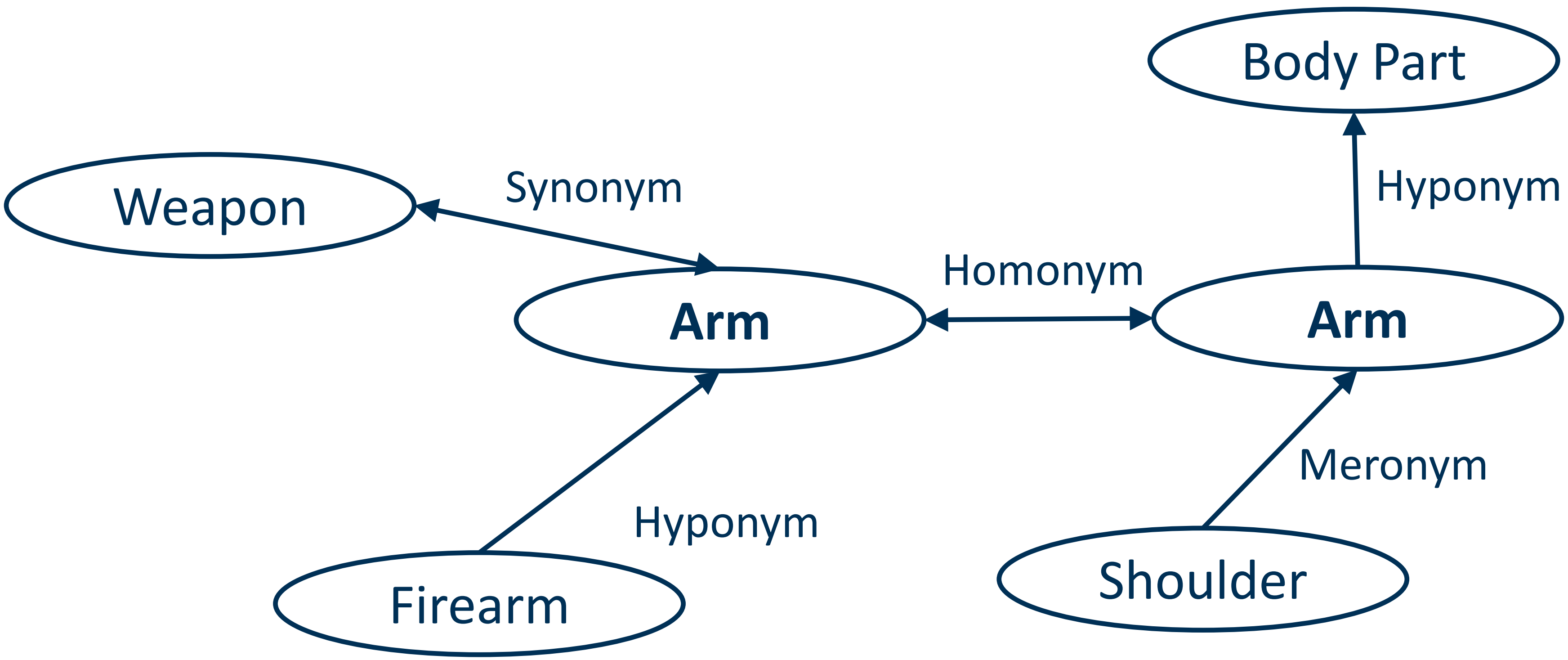
So, how do Semantics Work?

- Lexical semantics
  - Meaning of a word is defined by relations to other words
- Extensional semantics
  - Meaning of a word is defined by the set of its instances
- Intensional semantics, e.g., feature-based semantics
  - Meaning of a word is defined by features of the instances
- Prototype semantics
  - Meaning of a word is defined by proximity to a prototypical instance
- ...

- Each type of semantic is discussed in the following slides

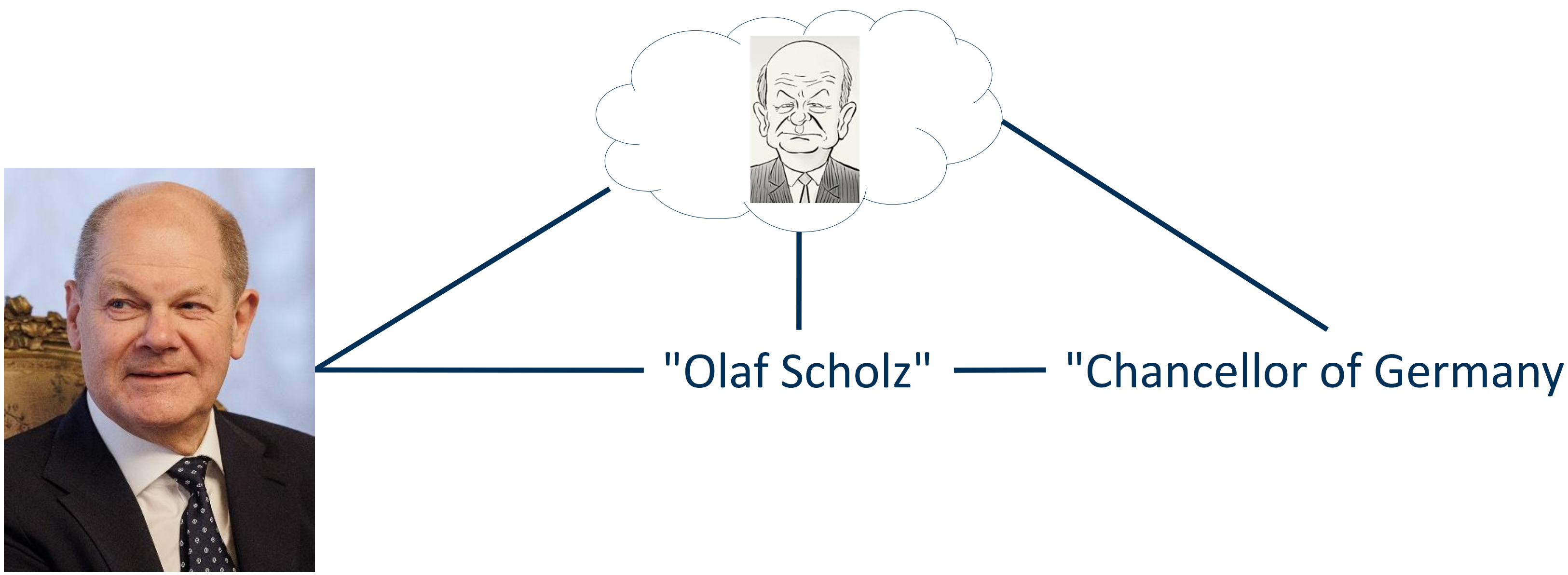
Lexical Semantics

- Defining semantics by establishing relations between words



Extensional Semantics

- Listing instances
  - EU members are Austria, Belgium, Bulgaria, …, Sweden.
- *Olaf Scholz == Chancellor of Germany*
  - both terms have the same extension



https://commons.wikimedia.org/wiki/File:Olaf_Scholz_2024.jpg

Intensional Semantics

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- Describes features of things, i.e., *semes*
- A seme is a feature that distinguishes the meaning of two words

Word	has wings	can swim	has fur	can fly
Duck	+	+	-	+
Bird	+	O	-	O
Bee	+	-	-	+
Dolphin	-	+	-	-
…				

Intensional vs. Extensional Semantics

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- Intensionally different things can have the same extension
- Classic example: morning star and evening star

Word	Celestial body	bright	visible in the morning	visible in the evening
Morning star	+	+	+	-
Evening star	+	+	-	+
…				

- both have the same extension (i.e., Venus)

Intensional vs. Extensional Semantics

- The extension can change over time without the intension changing
  - e.g., “student”
  - does that change the semantics?
- Intension may also change over time
  - technological achievements (e.g., intension of *ship*)
  - changes in moral values (e.g., intension of *marriage*)
- Extension may also be empty, e.g.
  - Unicorn
  - Martian
  - Yeti (?)

Intensional vs. Extensional Semantics

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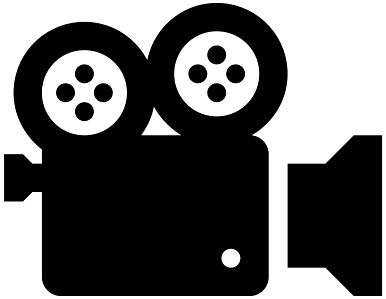
- ...explained by two well-known experts in the field :-)



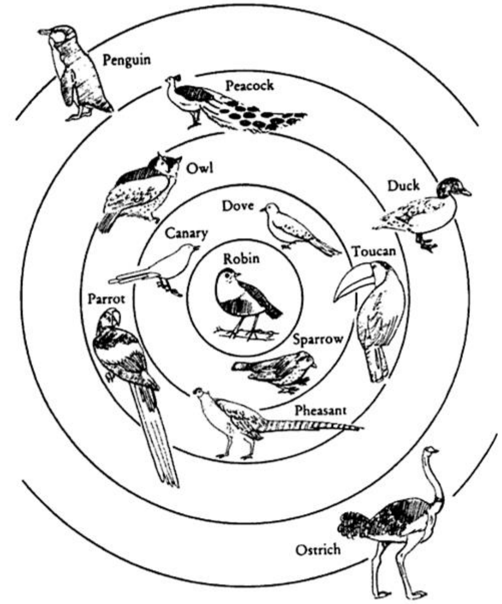
https://www.youtube.com/watch?v=o8TVAhMQQZg
https://www.youtube.com/watch?v=dvTFv5xJUQc

Prototype Semantics

- A small experiment:
  - Close your eyes, and imagine a bird!

Prototype Semantics

- So far, intensional and extensional semantics
  are based on boolean logics (i.e., there's only “true” and “false”)
- Prototype Semantics: a more fuzzy variant



Jean Aitchison: Words in the Mind (1987)

Semantic Shift

“Mask” 2019

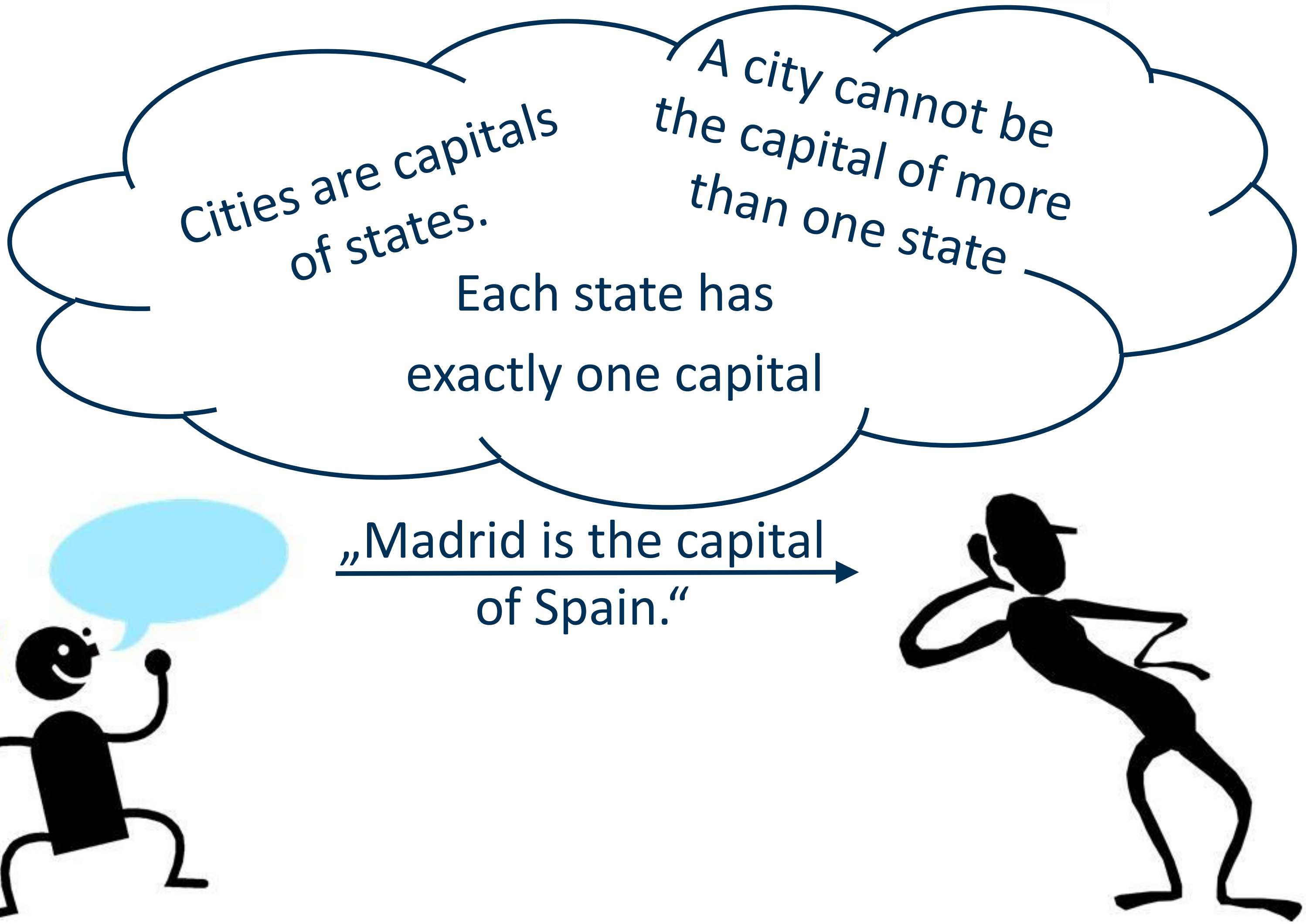
“Mask” 2022

How do Semantics Work?

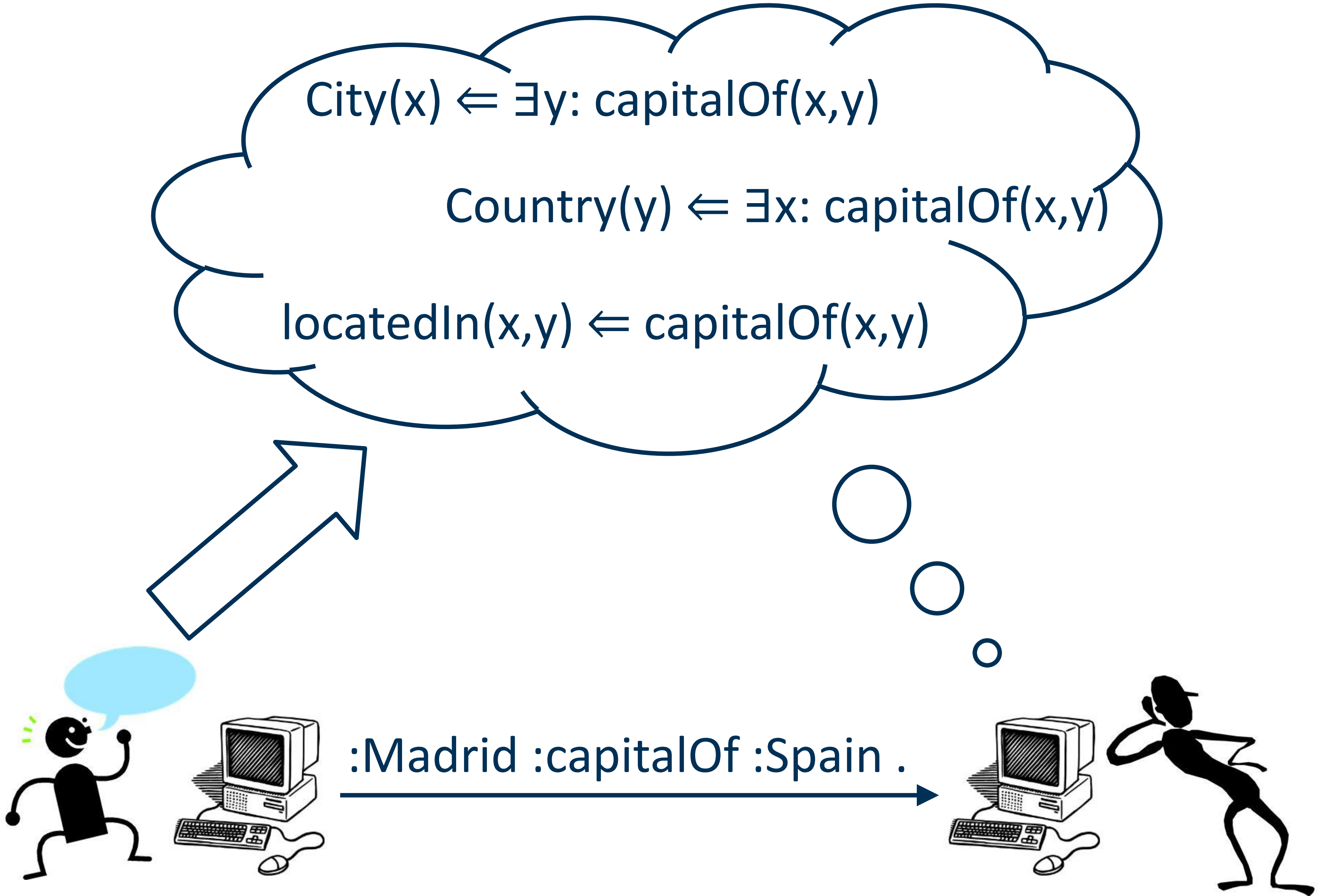
- We have learned: Semantics define the meaning of words
- That is what we do with ontologies
  - Using methods from lexical, intensional, and extensional semantics

http://walkinthewords.blogspot.com/2008/05/linguistic-cartoon-favorites-semantics.html

How do Semantics Work?



Semantics Formalized



Semantics Formalized

$$\text{City}(x) \Leftarrow \exists y: \text{capitalOf}(x,y)$$

$$\text{Country}(y) \Leftarrow \exists x: \text{capitalOf}(x,y)$$

$$\text{locatedIn}(x,y) \Leftarrow \text{capitalOf}(x,y)$$

- "An ontology is an explicit specification of a conceptualization."

Gruber (1993): Toward Principles for the Design of Ontologies Used for Knowledge Sharing. In: International Journal Human-Computer Studies Vol. 43, Issues 5-6, pp. 907-928.

- Ontologies encode the knowledge about a domain
- They form a common vocabulary
  - and describe the semantics of its terms

What is an Ontology?

- Ontology (without *a* or *the*) is the philosophical study of being
  - greek: *όντος* (things that are), *λόγος* (the study)
  - A sub discipline of philosophy

- In computer science (with *a* or *the*)
  - A formalized description of a domain
  - A shared vocabulary
  - A logical theory

Ontologies – Further Definitions

- Guarino und Giaretta (1995):

  "a logical theory which gives an **explicit**, **partial** account of a conceptualization"

- Uschold und Gruninger (1996):

  "**shared** understanding of some domain of interest"
  "an **explicit** account or representation of some **part of** a conceptualisation"

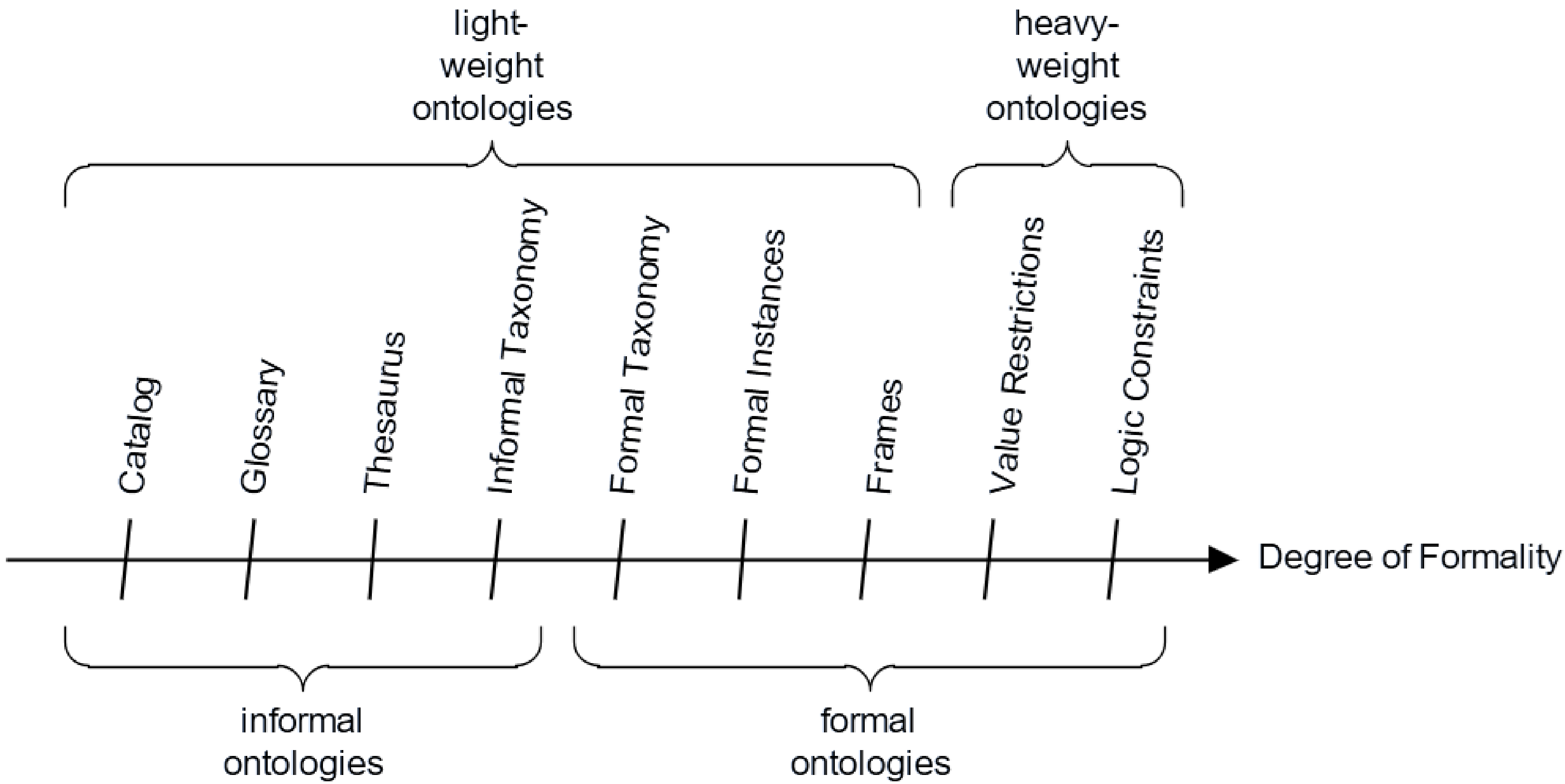
- Guarino (1998):

  "a set of **logical axioms** designed to account for the intended meaning of a vocabulary"

Essential Properties of Ontologies

- Explicit
  - Meaning is not “hidden” between the lines
- Formal
  - e.g., using logic or rule languages
- Shared
  - An ontology just for one person does not make much sense
- Partial
  - There will (probably) never be a full ontology of everything in the world

Classifications of Ontologies



Lassila & McGuiness (2001): The Role of Frame-Based Representation on the Semantic Web.
In: Linköping Electronic Articles in Computer and Information Science 6(5).

Classifications of Ontologies

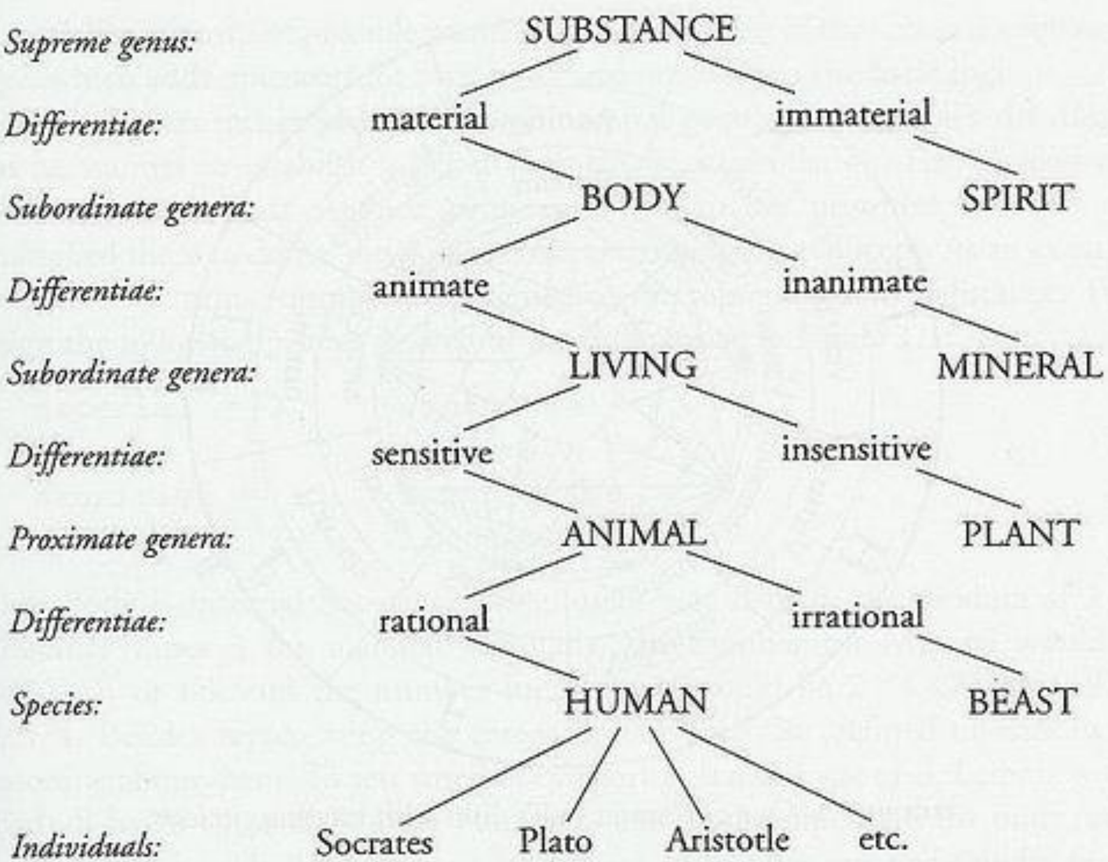


FIGURE 1.1 Tree of Porphyry, translated from a version by Peter of Spain (1239)

Porphyry, Greek philosopher, ca. 234-305

Encoding Simple Ontologies: RDFS

- A W3C Standard since 2004

- Most important element: classes

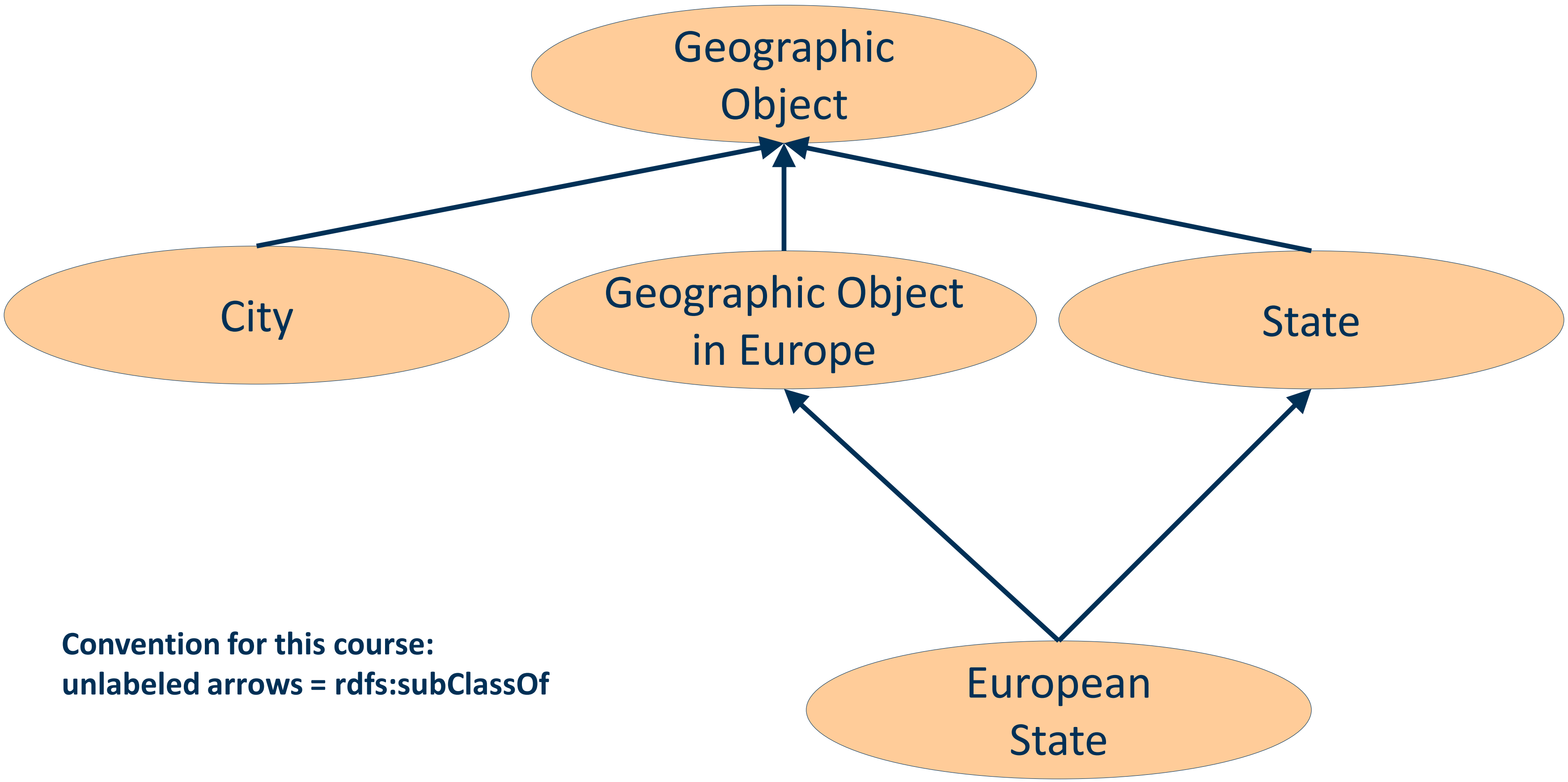
```
:State a rdfs:Class .
```

- Classes form hierarchies

```
:EuropeanState rdfs:subClassOf :State .
```

Class Hierarchies in RDF Schema

- Multiple inheritance is possible



Convention for this course:
unlabeled arrows = rdfs:subClassOf

Properties in RDF Schema

- Properties are the other important element
- Resemble two-valued predicates in predicate logic

```
:Madrid :capitalOf :Spain .
:capitalOf a rdf:Property .
```

- Properties also form hierarchies

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

Domains and Ranges of Properties

- In general, properties exist independently from classes
  - i.e., they are *first class citizens*
  - this is different than OOP or ERM
- Defining the domain and range of a property:

```
:capitalOf rdfs:domain :City .
:capitalOf rdfs:range :Country .
```

- Domain and range are inherited by sub properties
  - They can also be further restricted

Predefined Properties

- We have already seen

  `rdf:type`

  `rdfs:subClassOf`

  `rdfs:subPropertyOf`

  `rdfs:domain`

  `rdfs:range`

Further Predefined Properties

- Labels:

```
:Germany rdfs:label "Deutschland"@de .
:Germany rdfs:label "Germany"@en .
```

- Comments:

```
:Germany rdfs:comment "Germany as a political
  entity."@en .
```

- Links to other resources:

```
:Germany rdfs:seeAlso <http://www.deutschland.de/>
  .
```

- Link to defining schema:

```
:Country rdfs:isDefinedBy
  <http://foo.bar/countries.rdfs> .
```

URIs vs. Labels

- A URI is only a unique identifier
  - It does not need to be interpretable
  - `http://www.countries.org/4327893`

- Labels are made for human interpretation
- ...and can come in different languages:

```
countries:4327893 rfds:label "Deutschland"@de .
countries:4327893 rdfs:label "Germany"@en .
countries:4327893 rdfs:label "Tyskland"@sv .
...
```

URIs vs. Labels

- Labels and comments can also be assigned to RDFS elements:

```
:Country a rdfs:Class.
:Country rdfs:label "Land"@de.
:Country rdfs:label "Country"@en.

:locatedIn a rdf:Property .
:locatedIn rdfs:label "liegt in"@de.
:locatedIn rdfs:label "is located in"@en.
:locatedIn rdfs:comment "refers to geography"@en.
```

RDF Schema and RDF

- Every RDF Schema document is also an RDF document
- This means: all properties of RDF also hold for RDFS!

- Non-unique Naming Assumption

```
schema1:Country a rdfs:Class .
schema2:State a rdfs:Class .
```

- Open World Assumption

```
:Country rdfs:subClassOf :GeographicObject .
:City rdfs:subClassOf : GeographicObject .
```

Our First Ontology

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- States, cities, and capitals

```
:State a rdfs:Class .
:City a rdfs:Class .
:locatedIn a rdf:Property .
:capitalOf rdfs:subPropertyOf :locatedIn .
:capitalOf rdfs:domain :City .
:capitalOf rdfs:range :State .
```

Definition of the Terminology (T-Box)

```
:Madrid :capitalOf :Spain .
```

Definition of the Assertions (A-box)

What do We Gain Now?

:Country a rdfs:Class .
:City a rdfs:Class .
:locatedIn a rdfs:Property .
:capitalOf rdfs:subPropertyOf :locatedIn .
:capitalOf rdfs:domain :City .
:capitalOf rdfs:range :Country .

What do We Gain Now?


```
  :Madrid :capitalOf :Spain .
+ :capitalOf rdfs:domain :City
→ :Madrid a :City .
```

```
  :Madrid :capitalOf :Spain .
+ :capitalOf rdfs:range:Country
→ :Spain a :Country .
```

```
  :Madrid :capitalOf :Spain .
+ :capitalOf rdfs:subPropertyOf :locatedIn .
→ :Madrid :locatedIn :Spain .
```

Reasoning with RDF

- RDF Schema allows for *deductive* reasoning on RDF
- This means:
  - given facts and rules,
  - we can derive new facts
- The corresponding tools are called *reasoner*

- Opposite of deduction: *induction*
  - deriving models from facts
  - see, e.g., lectures on data mining and machine learning

A Bit of History

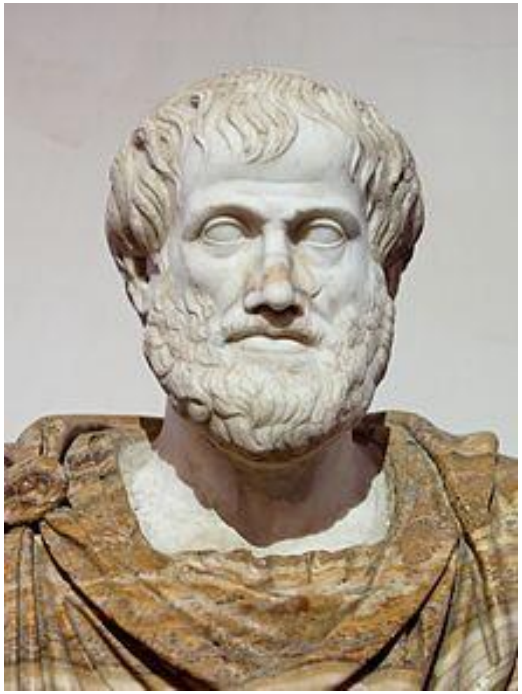
- Aristotle (384 – 322 BC)
- Syllogisms
  - Deriving facts using rules

- Example:

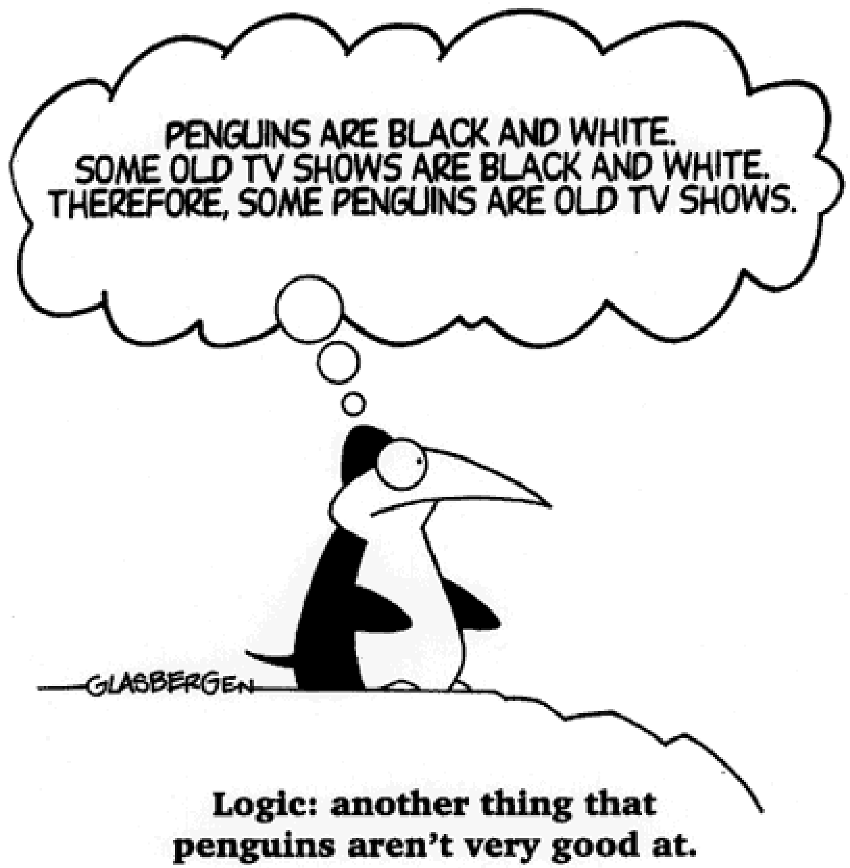
  All men are mortal.

  Socrates is a man.

  → Socrates is mortal.



A Bit of History



Interpretation and Entailment

- Entailment
  - The set of all consequences of a graph

- Mapping a graph to an entailment is called *interpretation*

- Simplest Interpretation:
  - <s,p,o> ∈ G → <s,p,o> ∈ Entailment

- This interpretation creates all statements explicitly contained in the graph.
- But the *implicit* statements are the interesting ones!

Interpretation using Deduction Rules

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- RDF interpretation can be done using RDFS deduction rules
- Those create an entailment
  - using existing resources, literals, and properties
  - creating additional triples like <s,p,o>
  - e.g.,
    - <Madrid, rdf:type, City>
    - <Madrid, located_in, Spain>
- Note:
  - no *new* resources, literals, or properties are created!

Reasoning with Deduction Rules

- Deduction rules are an interpretation function
- Simple reasoning algorithm (a.k.a. *forward chaining*):

```
Given: an RDF Graph G and
       a set of deduction rules R
Entailment E = G
Repeat
     M := { }
     For all rules in R
            For each statement S in E
                   Apply R to S
                   If E does not contain consequence
                          Add consequence to M
     Add all elements in M to E
until M = { }
```

Deduction Rules RDF Schema (Selection)

ID	Condition	Consequence
rdfs2	`s p o .` `p rdfs:domain c .`	`s rdf:type c .`
rdfs3	`s p o .` `p rdfs:range c .`	`o rdf:type c .`
rdfs7	`p1 rdfs:subPropertyOf p2 .` `s p1 o .`	`s p2 o.`
rdfs9	`s rdf:type c1 .` `c1 rdfs:subClassOf c2 .`	`s rdf:type c2 .`
rdfs10	`c rdf:type rdfs:Class .`	`c rdfs:subClassOf c .`
rdfs11	`c1 rdfs:subClassOf c2 .` `c2 rdfs:subClassOf c3 .`	`c1 rdfs:subClassOf c3 .`

`rdfs:subclassOf` is reflexive and transitive (same for `rdfs:subPropertyOf`)

W3C (2004): *RDF Semantics.* http://www.w3.org/TR/rdf-mt/ (Section 7.3 RDFS Entailment Rules)

Applying Deduction Rules

- Example:

```
:Employee a rdfs:Class .
:Employee rdfs:subClassOf :Human .
:Room a rdfs:Class .
:worksIn rdfs:subPropertyOf :hasOffice .
:hasOffice rdfs:domain :Employee .
:hasOffice rdfs:range :Room .

:Tim :worksIn :B626B01 .
```

Applying Deduction Rules

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- Example:

```
s=   :Tim
p1=  :worksIn
o=   :B626B01
p2=  :hasOffice
```

```
:worksIn rdfs:subPropertyOf :hasOffice .
:Tim :worksIn :B626B01 .
```

ID	Condition	Consequence
rdfs7	p1 rdfs:subPropertyOf p2 . s p1 o .	s p2 o.

- → :Tim :hasOffice :B626B01 .

Applying Deduction Rules

- Example:

```
s=  :Tim
p=  :hasOffice
o=  :B626B01
c=  :Employee
```

```
:Tim :hasOffice :B626B01 .
:hasOffice rdfs:domain :Employee .
```

ID	Condition	Consequence
rdfs2	s p o . p rdfs:domain c .	s rdf:type c .

→ :Tim rdf:type :Employee .

Applying Deduction Rules

- Example:

```
s=  :Tim
c1=:Employee
c2=:Human
```

```
:Tim rdf:type :Employee.
:Employee rdfs:subClassOf :Human .
```

ID	Condition	Consequence
rdfs9	s rdf:type c1 . c1 rdfs:subClassOf c2 .	s rdf:type c2 .

→ :Tim rdf:type :Human .

Forward Chaining

- Example revisited:

```
:Employee a rdfs:Class .
:Employee rdfs:subClassOf :Human .
:Room a rdfs:Class .
:worksIn rdfs:subPropertyOf :hasOffice .
:hasOffice rdfs:domain :Employee .
:hasOffice rdfs:range :Room .

:Tim :worksIn :B626B01 .

→ :Tim hasOffice :B626B01 .
→ :Tim rdf:type Employee .
→ :Tim rdf:type Human .
```

What if there are Multiple Domains/ Ranges?

- Example for social networks:

```
:knows rdfs:domain :Person .
:knows rdfs:domain :MemberOfSocialNetwork .
```

- What should be the semantics here?
  - Everybody who knows someone
    is a person *and* a member of a social network
  - Everybody who knows someone
    is a person *or* a member of a social network

The Rules will Tell Us

```
              :knows rdfs:domain :Person.                          (a0)
              :knows rdfs:domain :MemberOfSocialNetwork .(a1)
              :Peter :knows :Stephen .                             (a2)
(rdfs2+a0+a2) :Peter rdf:type :Person .                            (a3)
(rdfs2+a1+a2) :Peter rdf:type :MemberOfSocialNetwork .             (a4)
              ...
```

- This chain works for each object
  - it is always contained in both classes

    → i.e., the intersection semantics hold

What have We Gained?

- 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." ✗
  - ...

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!

What we Cannot Express (up to Now)

- "Every state has exactly one capital"
  - i.e., "A state cannot have more than one capital."
- “Every city can only be the capital of one state."
  - i.e., "A city cannot be the capital of two different states.”
- "A city cannot be a state at the same time."

What we Cannot Express (up to Now)

- Note: there is no negation in RDF and RDFS

- This means, we cannot produce any contradictions
  - This makes reasoning easy
  - But it also restricts the utility
  - Example:

    Mammals do not lay eggs

    Penguins lay eggs

    → Penguins are not mammals

- We will get to know formalisms that support negation
  - and learn how to do reasoning with them

What we Cannot Express (up to Now)

- The missing negation perfectly fits the AAA principle
  - Anybody can say anything about anything
- ...and the Open World Assumption

- Any new knowledge will always fit to the knowledge that is already there
  - This principle is called “monotonicity”

What we Cannot Express (up to Now)

- Kurt Gödel (1906-1978)
- Logic systems are either
  - not very powerful or
  - not free of contradictions
- RDF Schmea belongs to the first class

What we Cannot Express (up to Now)

- Jim Hendler (*1957)

- "A little semantics goes a long way."

Just a moment

- "We cannot produce any contradictions"
- so what about

  :Peter a :Baby .

  :Peter a :Adult .

- That is a contradiction!

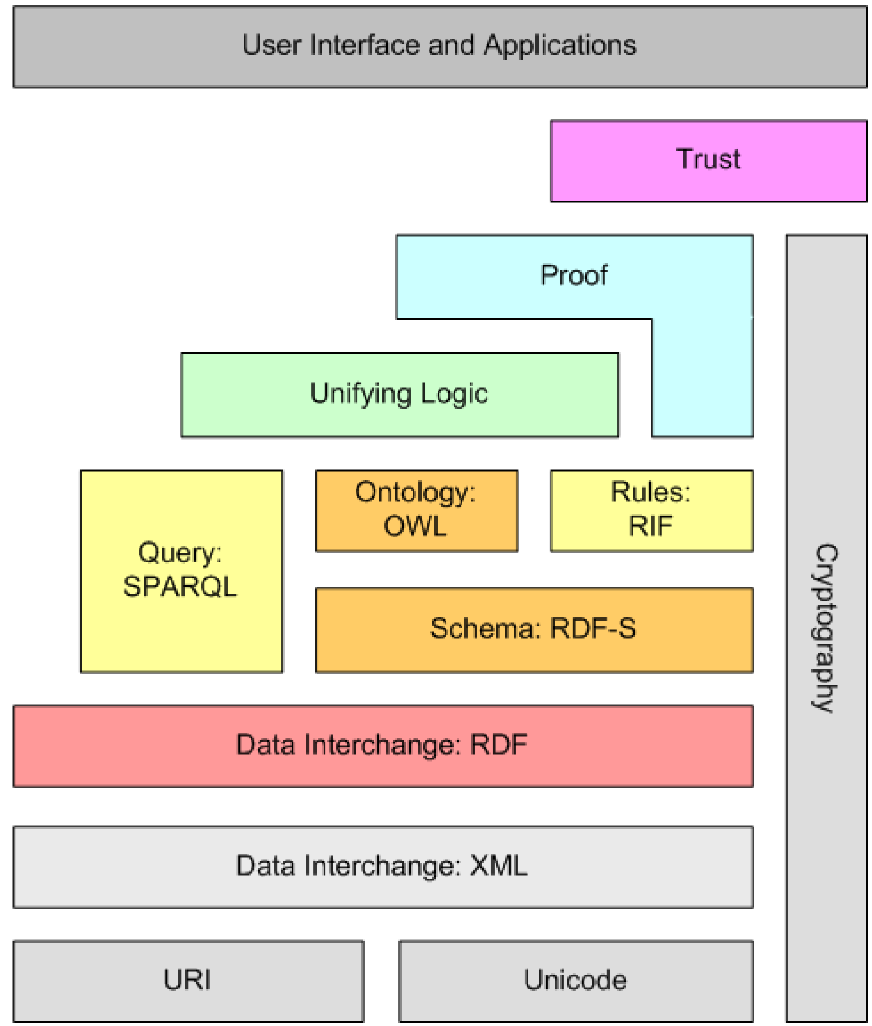
- Well, it is – for us human beings
- But a computer will not know
  - Non-unique name assumption!

The Semantic Web 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/

Questions?