

Symbolic AI

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Photo by Vasilyev Alexandr

Acknowledgements

- Based on the slides from:
 - Introduction to the Semantic Web (Fensel, STI Course)
 - Julia Hirschberg.
 - Pascal Hitzler.
 - Gerhard Weikum.
 - Ian Horrocks, CS6795 Semantic Web Techniques.

Today

- Knowledge Bases for supporting AI Systems.
- Knowledge Representation paradigms for KBs.



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[BRIEF-Avio receives EUR 40 mln financing from European Investment Bank <SPA2.MI>](#)

Companies: Avio SPA 80%, Avio SPA 80%, Avio SPA 80%

Topics: Business Finance, Contracts / Business Deals Events: ContactDetails

Industry: Spacecraft Manufacturing

Publication date: Oct 6, 2017 10:24:02 AM

Airbus SE

BAE Systems PLC

Boeing Co

[BRIEF-Airtelis orders three H215 Airbus Helicopters<AIR.PA><AIRG.DE>](#)

Companies: Airbus Helicopters SAS 50%, Airbus Helicopters SAS 50%, Airbus Helicopters SAS 50%

Topics: N/A Events: BusinessRelation

Industry: Aerospace & Defense - NEC, Aircraft Parts Manufacturing - NEC

Publication date: Oct 4, 2017 10:46:00 AM

Raytheon Co

BAE Systems PLC

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[BRIEF-British Airline Pilots' Association - pilots union calls for investigation into collapse of Monarch Airlines<MONA.UL>](#)

Companies: Monarch Airlines Ltd 80%, Monarch Airlines Ltd 80%, Monarch Airlines Ltd 80%

Topics: Other Events: N/A

Industry: Airlines - NEC

Publication date: Oct 9, 2017 1:55:13 PM

Raytheon Co

BAE Systems PLC

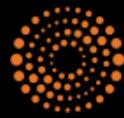
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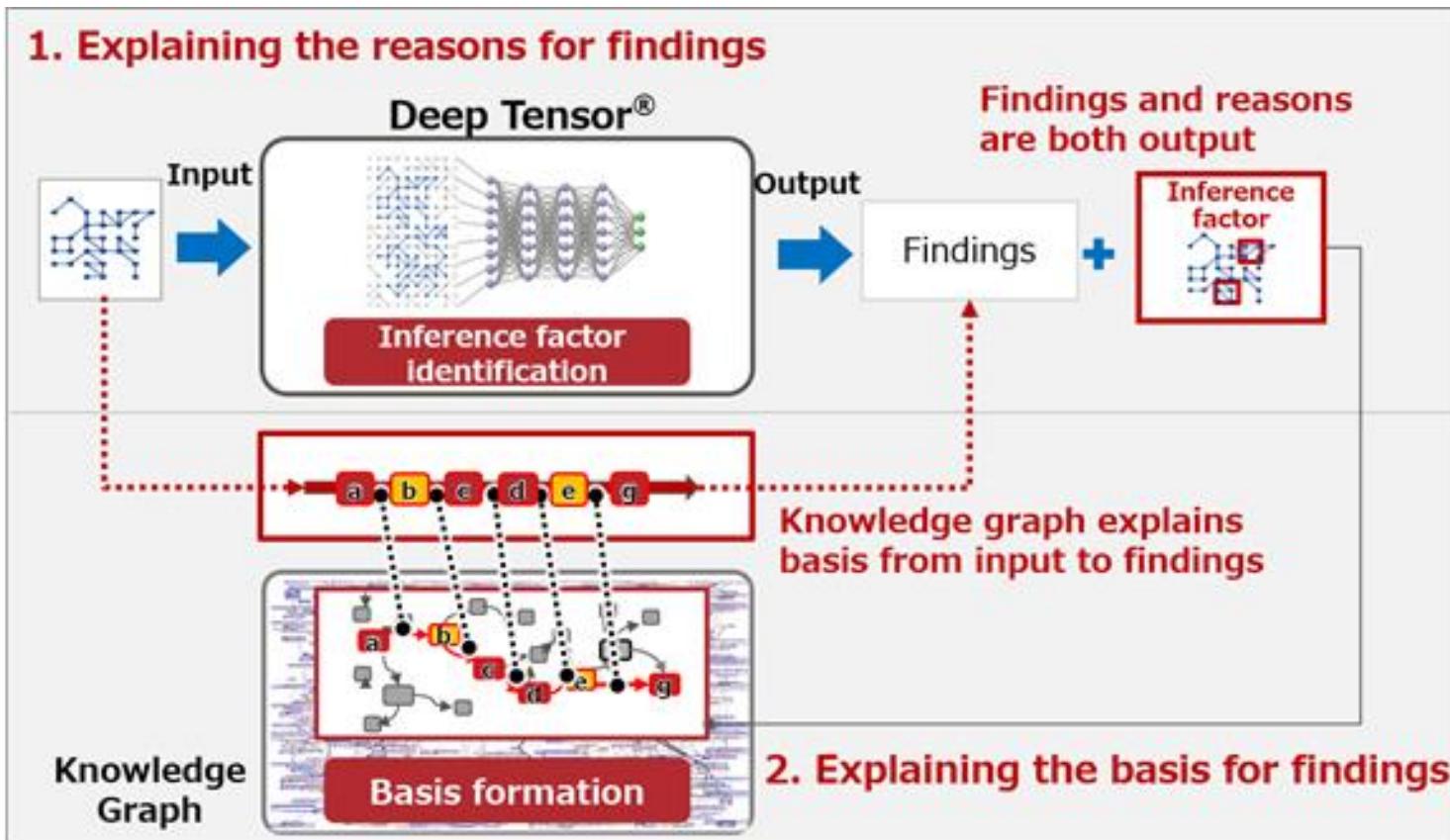
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Oct 6 (Reuters) - AVIO SPA <SPA2.MI> * SAYS SIGNED WITH EUROPEAN INVESTMENT BANK CONTRACT FOR EUR 40 MILLION FINANCING Source text for Eikon: [ID:nBIA5D9Ntk] Further company coverage: [SPA2.MI] (Gdynia Newsroom) (gdynia.newsroom@thomsonreuters.com; +48 58 772 0920 ;)



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Explainable Findings From Tensor Inferences Back to KGs



Machine Knowledge for Answer Engines

Weikum, 2019

Precise and concise answers
for advanced information needs:



properties of entity

- ★ Nobel laureate whose daughter also won a Nobel prize?



sets of entities

- ★ Pop singers who are also poets?

relationships between entities

- ★ Commonalities & relationships among:
Alan Turing, Paul Bocuse, Steve Jobs, Katherine Goble?



Machine Knowledge for Answer Engines

Weikum, 2019

**Precise and concise answers
for advanced information needs:**

real applications

- ★ Proteins that bind to the Zika virus?
- Polymer materials for super-capacitors?
- European politicians mentioned in Panama Leaks?

Representation

- **Representation**: organization of a perceptual/symbolic space into an abstraction
 - Attention/selection
 - Intent/goal
- Maximization of Inferential Locality
- Abstraction for Purpose
- Correctness/Completeness for Purpose

Good Knowledge Representation Languages

- Combines the best of natural and formal languages:
 - expressive
 - concise
 - unambiguous
 - independent of context
 - what you say today will still be interpretable tomorrow
 - efficient
 - the knowledge can be represented in a format that is suitable for computers
 - operational
 - there is an inference procedure which can act on it to make new sentences



Knowledge Graphs

Brief History of Knowledge Bases

Weikum, 2019



Vannevar Bush



Cyc



WordNet



Wikipedia



freebase™

DBpedia

yAGO
select knowledge

WIKIDATA

BabelNet

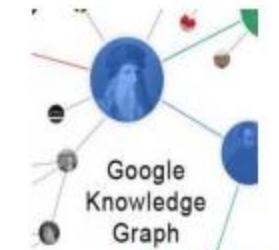


IBM Watson

amazon



SIEMENS



Terminology

- Ontology
 - provides more complete definitions for concepts
 - Graphical conceptual model
- Thesaurus
 - simple relationships between words
 - synonyms, homonyms, antonyms, etc.
 - often combined with a taxonomy
- Taxonomy
 - hierarchical arrangement of concepts
 - often used as a “backbone” for an ontology
- Lexicon
 - provides natural language descriptions of words and their meanings

Word Senses & Relations

Reminder: lemma and wordform

- A lemma or citation form
 - Same stem, part of speech, rough semantics
- A word form
 - The “inflected” word as it appears in text

Word form	Lemma
banks	bank
sung	sing
duermes	dormir

Lemmas have senses

- One lemma “bank” can have many meanings:

- Sense 1: • ...a **bank** can hold the investments in a custodial account...
 1
- Sense 2: • “...as agriculture burgeons on the east **bank** the river will shrink
 even more”
 2

- Sense (or word sense)
 - A discrete representation
of an aspect of a word’s meaning.
- The lemma **bank** here has two senses

Polysemy

- 1. The **bank** was constructed in 1875 out of local red brick.
- 2. I withdrew the money from the **bank**.
- Are those the same sense?
 - Sense 2: “A financial institution”
 - Sense 1: “The building belonging to a financial institution”
- A polysemous word has **related** meanings
 - Most non-rare words have multiple meanings.

How do we know when a word has more than one sense?

- The “zeugma” test: Two senses of **serve**?
 - Which flights **serve** breakfast?
 - Does Lufthansa **serve** Philadelphia?
 - ?Does Lufthansa serve breakfast and San Jose?
- Since this conjunction sounds weird,
 - we say that these are **two different senses of “serve”**

Synonyms

- Word that have the same meaning in some or all contexts:
 - couch / sofa
 - big / large
 - automobile / car
 - vomit / throw up
 - Water / H₂O
- Two lexemes are synonyms:
 - if they can be substituted for each other in all situations.
 - If so they have the same **propositional meaning.**

Synonymy is a relation between senses rather than words

- Consider the words *big* and *large*.
- Are they synonyms?
 - How **big** is that plane?
 - Would I be flying on a **large** or small plane?
- How about here:
 - Miss Nelson became a kind of **big** sister to Benjamin.
 - ?Miss Nelson became a kind of **large** sister to Benjamin.
- Why?
 - *big* has a sense that means being older, or grown up.
 - *large* lacks this sense.

Antonyms

- Senses that are opposites with respect to one feature of meaning.
- Otherwise, they are very similar!

dark/light short/long fast/slow rise/fall

hot/cold up/down in/out

Hyponymy and Hypernymy

- One sense is a hyponym of another if the first sense is more specific, denoting a subclass of the other:
 - *car* is a hyponym of *vehicle*
 - *mango* is a hyponym of *fruit*
- Conversely hypernym/superordinate (“hyper is super”):
 - *vehicle* is a hypernym of *car*
 - *fruit* is a hypernym of *mango*

Superordinate/hyper	vehicle	fruit	furniture
Subordinate/hyponym	car	mango	chair

Hyponymy more formally

- Extensional:
 - The class denoted by the superordinate extensionally includes the class denoted by the hyponym.
- Hyponymy is usually transitive
 - (A hypo B and B hypo C entails A hypo C).
- Another name: the IS-A hierarchy:
 - A IS-A B (or A ISA B)
 - B **subsumes** A

Hyponyms and Instances

- WordNet has both classes and instances.
- An instance is an individual, a proper noun that is a unique entity:
 - San Francisco is an **instance** of city
 - But city is a class
 - city is a **hyponym** of municipality...location...

WordNet & Other Online Thesauri

Senses of “bass” in Wordnet

Noun

- S: (n) **bass** (the lowest part of the musical range)
- S: (n) **bass**, **bass part** (the lowest part in polyphonic music)
- S: (n) **bass**, **basso** (an adult male singer with the lowest voice)
- S: (n) **sea bass**, **bass** (the lean flesh of a saltwater fish of the family Serranidae)
- S: (n) **freshwater bass**, **bass** (any of various North American freshwater fish with lean flesh (especially of the genus Micropterus))
- S: (n) **bass**, **bass voice**, **basso** (the lowest adult male singing voice)
- S: (n) **bass** (the member with the lowest range of a family of musical instruments)
- S: (n) **bass** (nontechnical name for any of numerous edible marine and freshwater spiny-finned fishes)

Adjective

- S: (adj) **bass**, **deep** (having or denoting a low vocal or instrumental range) "a deep voice"; "a bass voice is lower than a baritone voice"; "a bass clarinet"

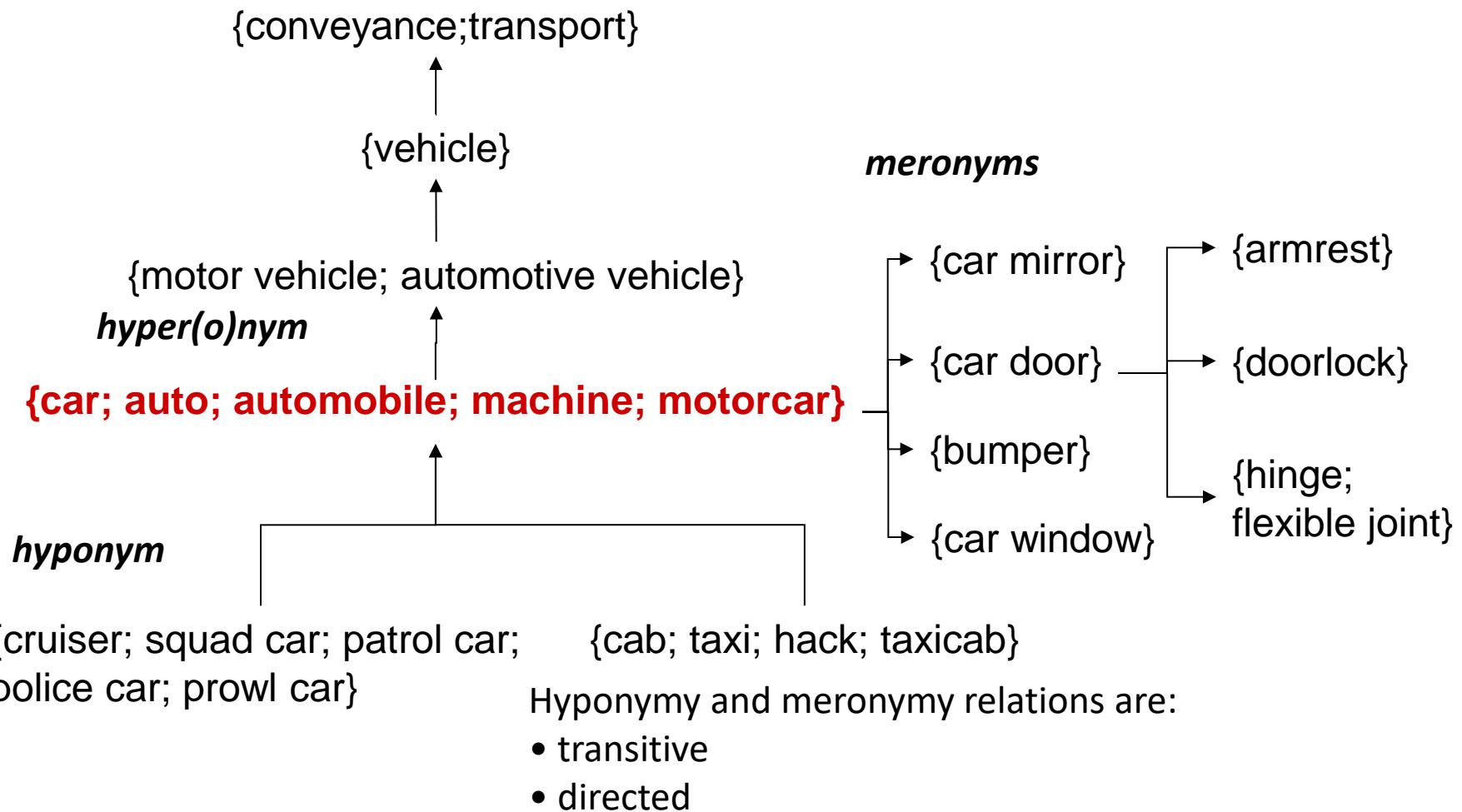
How is “sense” defined in WordNet?

- The synset (synonym set), the set of near-synonyms, instantiates a sense or concept, with a gloss.
- Example: chump as a noun with the gloss:
“a person who is gullible and easy to take advantage of”
- This sense of “chump” is shared by 9 words:
chump¹, fool², gull¹, mark⁹, patsy¹, fall guy¹, sucker¹, soft touch¹, mug²

WordNet Hypernym Hierarchy for “bass”

- S: (n) bass, basso (an adult male singer with the lowest voice)
 - direct hypernym / inherited hypernym / sister term
 - S: (n) singer, vocalist, vocalizer, vocaliser (a person who sings)
 - S: (n) musician, instrumentalist, player (someone who plays a musical instrument (as a profession))
 - S: (n) performer, performing artist (an entertainer who performs a dramatic or musical work for an audience)
 - S: (n) entertainer (a person who tries to please or amuse)
 - S: (n) person, individual, someone, somebody, mortal, soul (a human being) "there was too much for one person to do"
 - S: (n) organism, being (a living thing that has (or can develop) the ability to act or function independently)
 - S: (n) living thing, animate thing (a living (or once living) entity)
 - S: (n) whole, unit (an assemblage of parts that is regarded as a single entity) "how big is that part compared to the whole?"; "the team is a unit"
 - S: (n) object, physical object (a tangible and visible entity; an entity that can cast a shadow) "it was full of rackets, balls and other objects"
 - S: (n) physical entity (an entity that has physical existence)
 - S: (n) entity (that which is perceived or known or inferred to have its own distinct existence (living or nonliving))

Wordnet: a network of semantically related words



Wordnet Semantic Relations

WN 1.5 starting point

The ‘synset’ as a weak notion of synonymy:

“two expressions are synonymous in a linguistic context C if the substitution of one for the other in C does not alter the truth value.” (Miller et al. 1993)

Relations between synsets:

HYPONYMY	noun-to-noun	car/ vehicle
	verb-to-verb	walk/ move
MERONYMY	noun-to-noun	head/ nose
ANTONYMY	adjective-to-adjective	good/bad
	verb-to-verb	open/ close
ENTAILMENT	verb-to-verb	buy/ pay
CAUSE	verb-to-verb	kill/ die

Some observations on Wordnet

- Synsets are more compact representations for concepts than word meanings in traditional lexicons.
- Synonyms and hypernyms are substitutional variants:
 - begin – commence
 - I once had a **canary**. The **bird** got sick. The poor **animal** died.
- Hyponymy and meronymy chains are important transitive relations for predicting properties and explaining textual properties:
object -> artifact -> vehicle -> 4-wheeled vehicle -> car
- Strict separation of part of speech (PoS) although concepts are closely related (**bed – sleep**) and are similar (**dead – death**).

PoS (Part-of-Speech)

The Penn Treebank POS tagset.

1. CC	Coordinating conjunction	25. TO	<i>to</i>
2. CD	Cardinal number	26. UH	Interjection
3. DT	Determiner	27. VB	Verb, base form
4. EX	Existential <i>there</i>	28. VBD	Verb, past tense
5. FW	Foreign word	29. VBG	Verb, gerund/present participle
6. IN	Preposition/subordinating conjunction	30. VBN	Verb, past participle
7. JJ	Adjective	31. VBP	Verb, non-3rd ps. sing. present
8. JJR	Adjective, comparative	32. VBZ	Verb, 3rd ps. sing. present
9. JJS	Adjective, superlative	33. WDT	<i>wh</i> -determiner
10. LS	List item marker	34. WP	<i>wh</i> -pronoun
11. MD	Modal	35. WP\$	Possessive <i>wh</i> -pronoun
12. NN	Noun, singular or mass	36. WRB	<i>wh</i> -adverb
13. NNS	Noun, plural	37. #	Pound sign
14. NNP	Proper noun, singular	38. \$	Dollar sign
15. NNPS	Proper noun, plural	39. .	Sentence-final punctuation
16. PDT	Predeterminer	40. ,	Comma
17. POS	Possessive ending	41. :	Colon, semi-colon
18. PRP	Personal pronoun	42. (Left bracket character
19. PP\$	Possessive pronoun	43.)	Right bracket character
20. RB	Adverb	44. "	Straight double quote
21. RBR	Adverb, comparative	45. '	Left open single quote
22. RBS	Adverb, superlative	46. "	Left open double quote
23. RP	Particle	47. '	Right close single quote
24. SYM	Symbol (mathematical or scientific)	48. "	Right close double quote

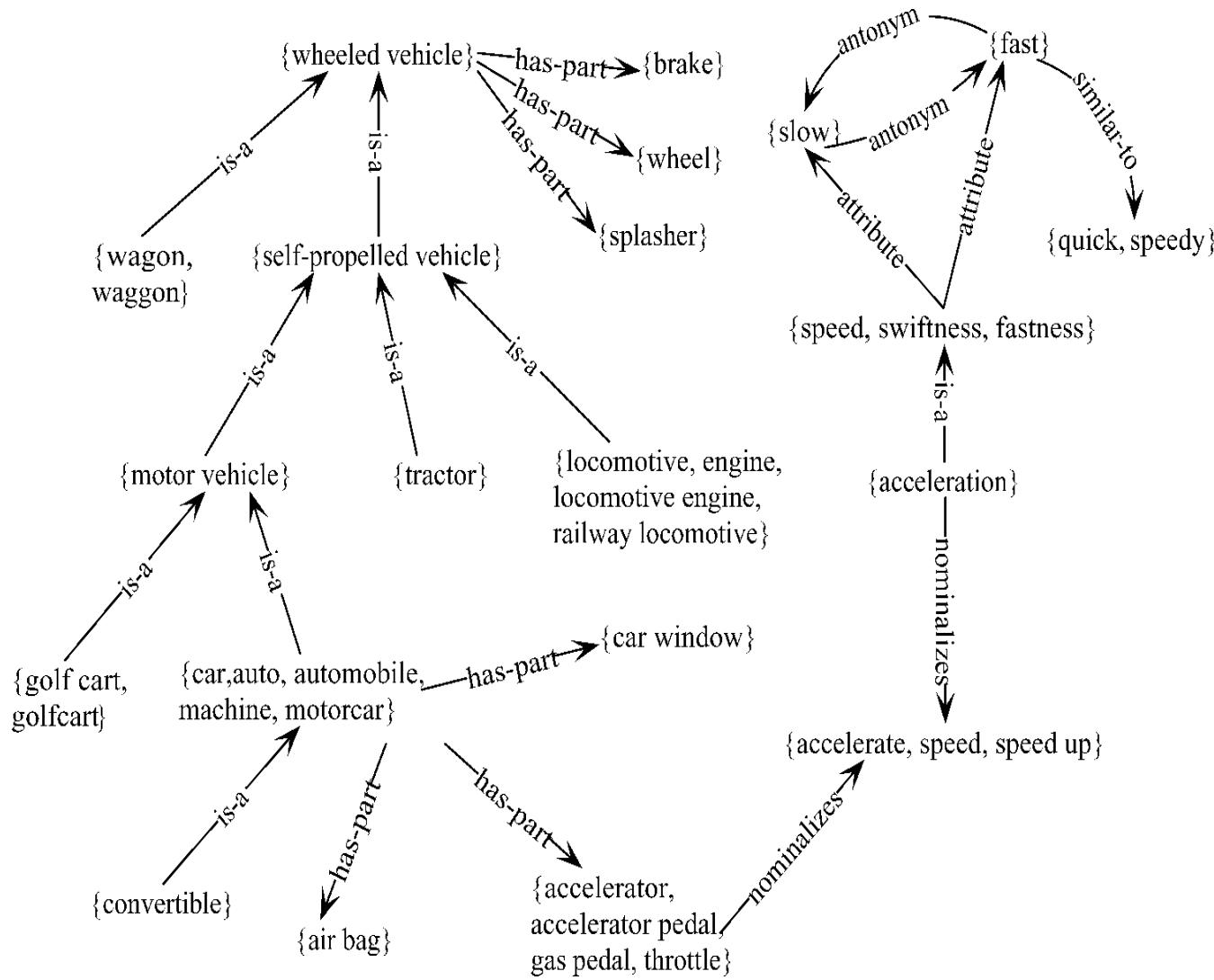
WordNet Noun Relations (Reference)

Relation	Also Called	Definition	Example
Hypernym	Superordinate	From concepts to superordinates	<i>breakfast</i> ¹ → <i>meal</i> ¹
Hyponym	Subordinate	From concepts to subtypes	<i>meal</i> ¹ → <i>lunch</i> ¹
Instance Hypernym	Instance	From instances to their concepts	<i>Austen</i> ¹ → <i>author</i> ¹
Instance Hyponym	Has-Instance	From concepts to concept instances	<i>composer</i> ¹ → <i>Bach</i> ¹
Member Meronym	Has-Member	From groups to their members	<i>faculty</i> ² → <i>professor</i> ¹
Member Holonym	Member-Of	From members to their groups	<i>copilot</i> ¹ → <i>crew</i> ¹
Part Meronym	Has-Part	From wholes to parts	<i>table</i> ² → <i>leg</i> ³
Part Holonym	Part-Of	From parts to wholes	<i>course</i> ⁷ → <i>meal</i> ¹
Substance Meronym		From substances to their subparts	<i>water</i> ¹ → <i>oxygen</i> ¹
Substance Holonym		From parts of substances to wholes	<i>gin</i> ¹ → <i>martini</i> ¹
Antonym		Semantic opposition between lemmas	<i>leader</i> ¹ ⇔ <i>follower</i> ¹
Derivationally		Lemmas w/same morphological root	<i>destruction</i> ¹ ⇔ <i>destroy</i> ¹
Related Form			

WordNet Verb Relations (Reference)

Relation	Definition	Example
Hypernym	From events to superordinate events	<i>fly</i> ⁹ → <i>travel</i> ⁵
Troponym	From events to subordinate event (often via specific manner)	<i>walk</i> ¹ → <i>stroll</i> ¹
Entails	From verbs (events) to the verbs (events) they entail	<i>snore</i> ¹ → <i>sleep</i> ¹
Antonym	Semantic opposition between lemmas	<i>increase</i> ¹ ⇔ <i>decrease</i> ¹
Derivationally	Lemmas with same morphological root	<i>destroy</i> ¹ ⇔ <i>destruction</i> ¹
Related Form		

WordNet: Viewed as a Graph



WordNet 3.0

- Where it is:
 - <http://wordnetweb.princeton.edu/perl/webwn>
- Libraries
 - Python: WordNet from NLTK
 - <http://www.nltk.org/Home>
 - Java:
 - JWNL, extJWNL on sourceforge

Extended WordNet (XWN)

- WordNet with syntactic and semantic annotations over its glosses.
- Contains logical forms and disambiguated glosses.
- XWN 2.0-1 is based on WordNet 2.0.

1. **excellent**, first-class, fantabulous -- (**of the highest quality**; "made an excellent speech"; "the school has excellent teachers"; "a first-class mind")

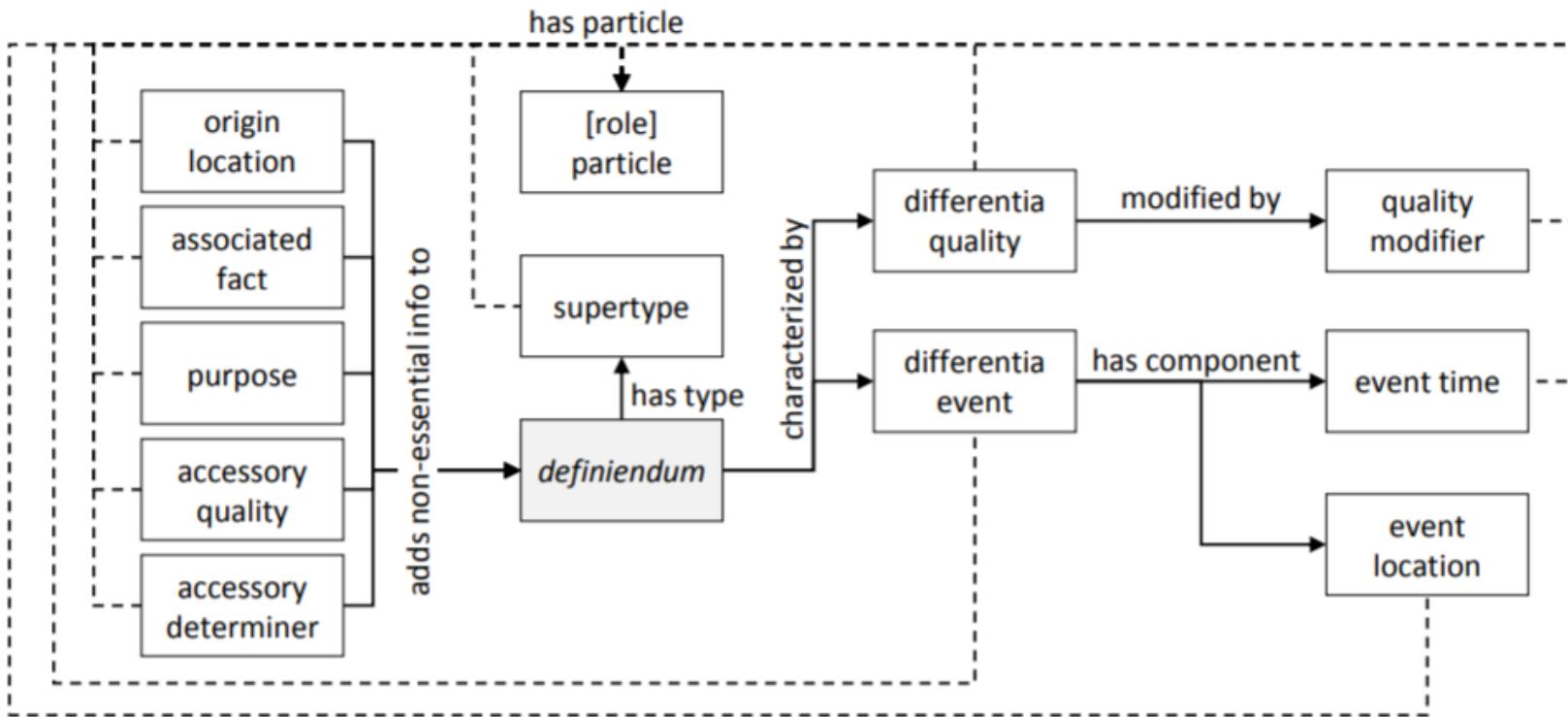
(TOP (S (NP (JJ **excellent**))
 (VP (VBZ **is**)
 (NP (NP (NN **something**))
 (PP (IN **of**)
 (NP (DT **the**) (JJS **highest**) (NN **quality**))))
 (.)))

excellent:JJ(x1) -> **of**:IN(x1, x2) **highest**:JJ(x1)
quality:NN(x1)

```
<wf pos="IN" >of</wf>
<wf pos="DT" >the</wf>
<wf pos="JJS" lemma="high" quality="silver" wnsn="1"
>highest</wf>
<wf pos="NN" lemma="quality" quality="normal" wnsn="2"
>quality</wf>
```

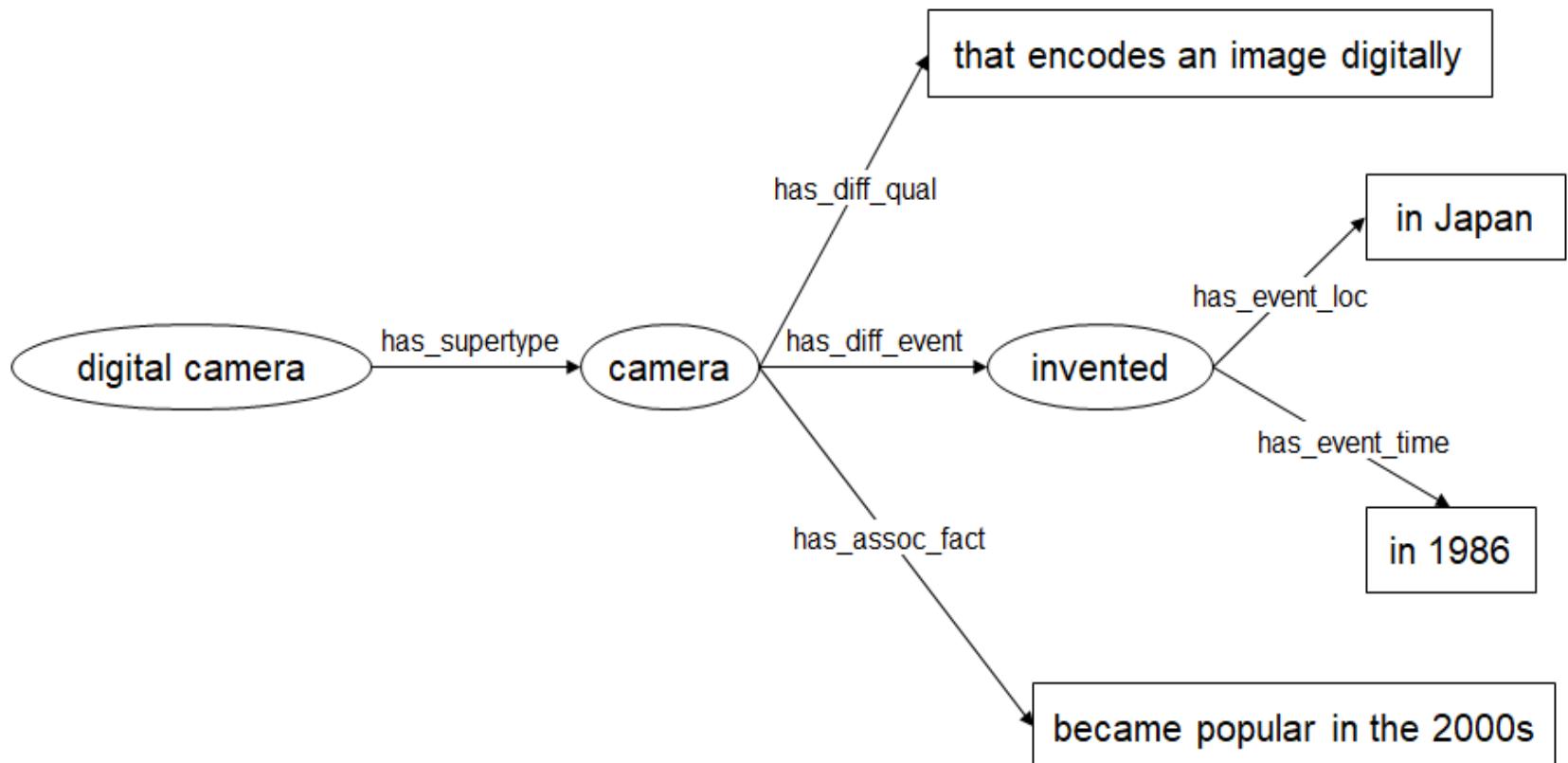
Semantic Roles for Lexical Definitions

Aristotle's classic theory of definition introduced important aspects such as the **genus-differentia definition pattern** and the **essential/non-essential property differentiation**.



Definition Graphs

digital camera: a camera invented in Japan in 1986 that encodes an image digitally and became popular in the 2000s



MeSH: Medical Subject Headings thesaurus from the National Library of Medicine

- **MeSH (Medical Subject Headings)**
 - 177,000 entry terms that correspond to 26,142 biomedical “headings”

Synset

- **Hemoglobins**

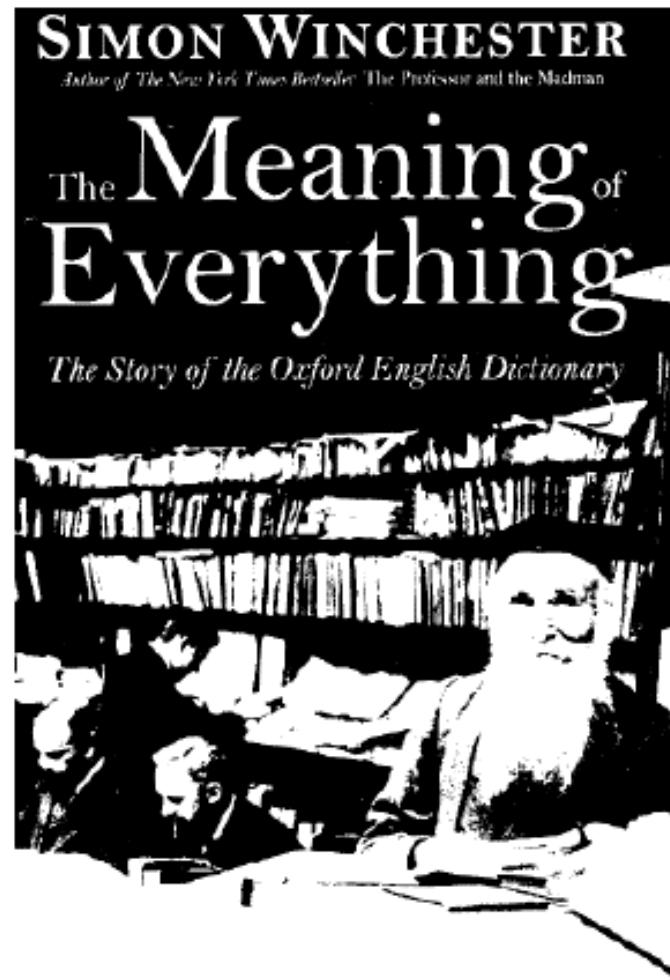
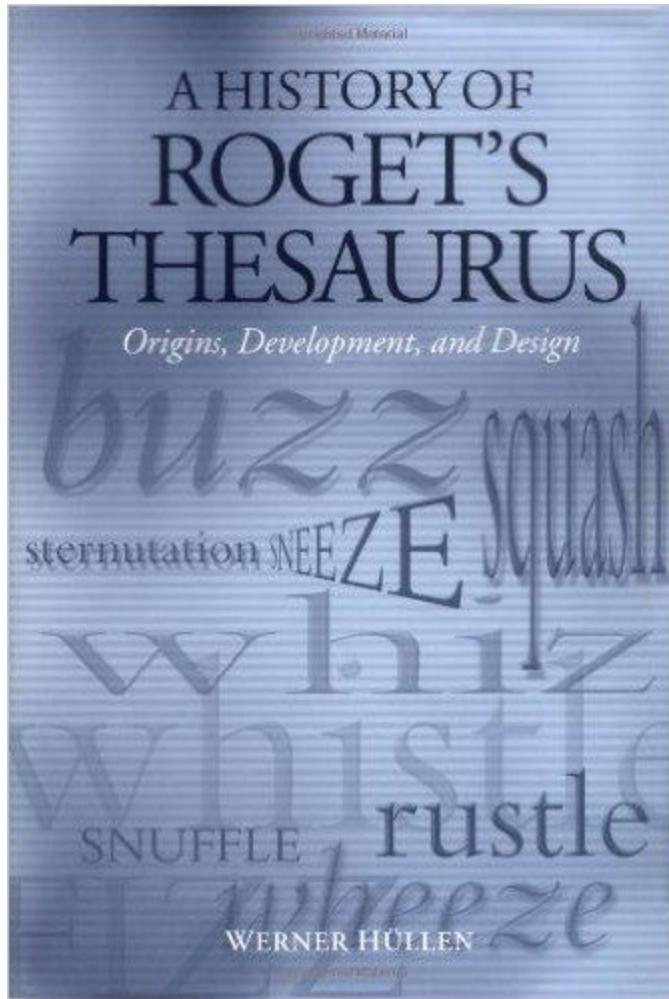
Entry Terms: Eryhem, Ferrous Hemoglobin, Hemoglobin

Definition: The oxygen-carrying proteins of ERYTHROCYTES. They are found in all vertebrates and some invertebrates. The number of globin subunits in the hemoglobin quaternary structure differs between species. Structures range from monomeric to a variety of multimeric arrangements

The MeSH Hierarchy

1. + Anatomy [A]
 2. + Organisms [B]
 3. + Diseases [C]
 4. - Chemicals and Drugs [D]
 - 1 o [Inorganic Chemicals \[D01\]](#) +
 - 2 o [Organic Chemicals \[D02\]](#) +
 - 3 o [Heterocyclic Compounds \[D03\]](#) +
 - 4 o [Polycyclic Compounds \[D04\]](#) +
 - 5 o [Macromolecular Substances \[D05\]](#) +
 - 6 o [Hormones, Hormone Substitutes, and](#)
 - 7 o [Enzymes and Coenzymes \[D08\]](#) +
 - 8 o [Carbohydrates \[D09\]](#) +
 - 9 o [Lipids \[D10\]](#) +
 - 10 o [Amino Acids, Peptides, and Proteins \[D11\]](#)
 - 11 o [Nucleic Acids, Nucleotides, and Nucleosides \[D12\]](#)
 - 12 o [Complex Mixtures \[D20\]](#) +
 - 13 o [Biological Factors \[D23\]](#) +
 - 14 o [Biomedical and Dental Materials \[D25\]](#)
 - 15 o [Pharmaceutical Preparations \[D26\]](#) +
 - 16 o [Chemical Actions and Uses \[D27\]](#) +
 5. + Analytical, Diagnostic and Therapeutic Techniques and Equipment [E]
 6. + Psychiatry and Psychology [F]
 7. + Phenomena and Processes [G]
- [Amino Acids, Peptides, and Proteins \[D12\]](#)
[Proteins \[D12.776\]](#)
[Blood Proteins \[D12.776.124\]](#)
[Acute-Phase Proteins \[D12.776.124.050\]](#) +
[Anion Exchange Protein 1, Erythrocyte \[D12.776.124.078\]](#)
[Ankyrins \[D12.776.124.080\]](#)
[beta 2-Glycoprotein I \[D12.776.124.117\]](#)
[Blood Coagulation Factors \[D12.776.124.125\]](#) +
[Cholesterol Ester Transfer Proteins \[D12.776.124.197\]](#)
[Fibrin \[D12.776.124.270\]](#) +
[Glycophorin \[D12.776.124.300\]](#)
[Hemocyanin \[D12.776.124.337\]](#)
► [Hemoglobins \[D12.776.124.400\]](#)
[Carboxyhemoglobin \[D12.776.124.400.141\]](#)
[Erythrocytins \[D12.776.124.400.220\]](#)

Curating Definitions: A Tour de Force



The theoretical distinction between dictionaries and encyclopaedias has traditionally been an issue of central importance for **lexicologists** (linguists who study word meaning) and **lexicographers** (dictionary writers).

The Dictionary View

- The dictionary view treats knowledge of word meaning as distinct from cultural knowledge, social knowledge and physical knowledge.
- Componential analysis or semantic decomposition approach:
 - word meaning is modelled in terms of semantic features or primitives.

bachelor is represented
as [MALE,ADULT,MARRIED]

Is the pope a *bachelor*?

Prototypes

“best example” of a category: e.g. *blackbird* vs. *penguin* for the category ‘bird’. But notice that the prototype may be abstract.



- not necessarily incompatible with feature theories
- fuzzy boundaries
- family resemblance



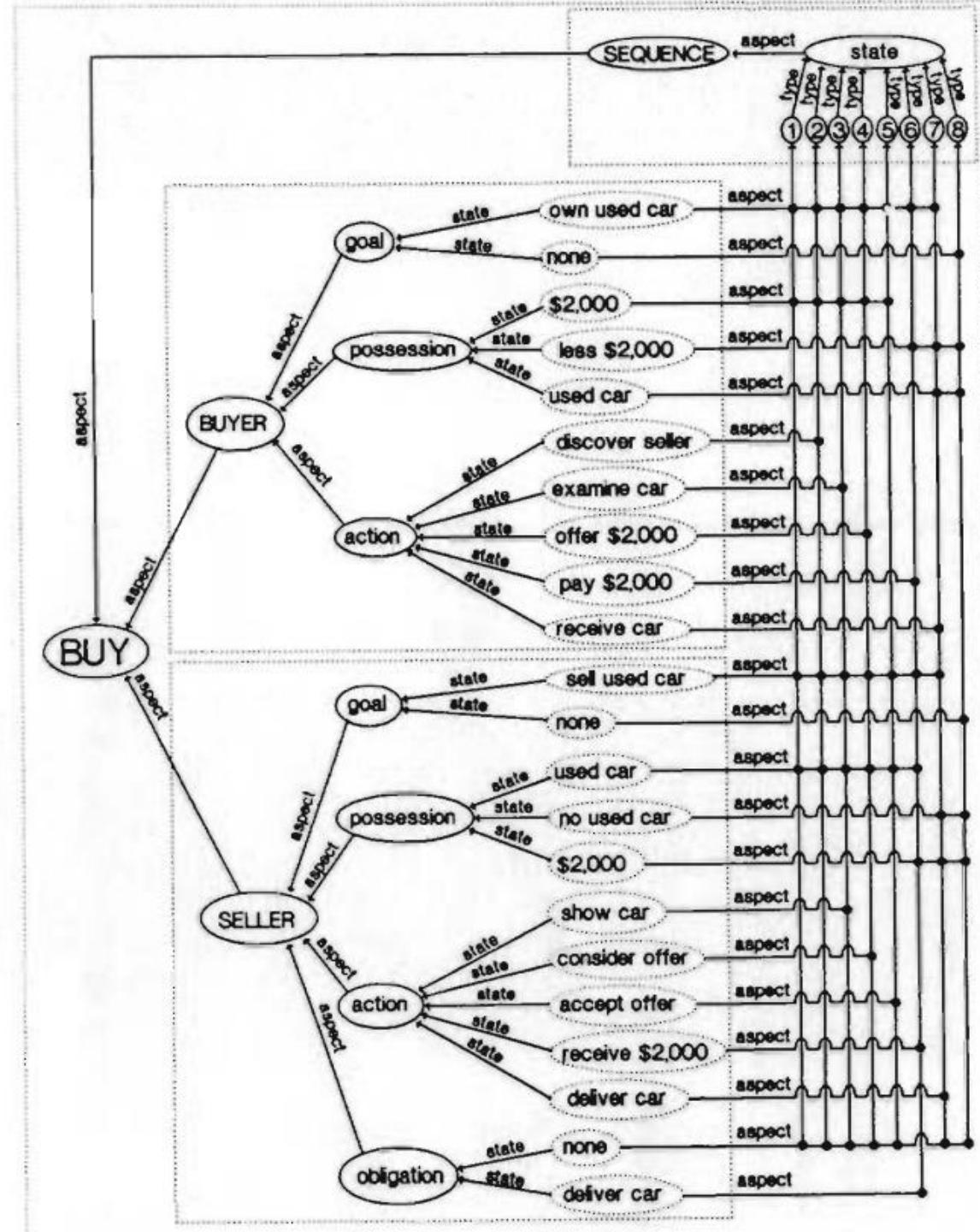
rank	category				
	BIRD	FRUIT	VEHICLE	FURNITURE	WEAPON
top eight					
1	robin	orange	automobile	chair	gun
2	sparrow	apple	station wagon	sofa	pistol
3	bluejay	banana	truck	couch	revolver
4	bluebird	peach	car	table	machine gun
5	canary	pear	bus	easy chair	rifle
6	blackbird	apricot	taxi	dresser	switchblade
7	dove	tangerine	jeep	rocking chair	knife
8	lark	plum	ambulance	coffee table	dagger
...
middle ranks					
26*	hawk	tangelo	subway	lamp	whip
27	raven	papaya	trailer	stool	ice pick
28	goldfinch	honeydew	cart	hassock	slingshot
29	parrot	fig	wheelchair	drawers	fists
30	sandpiper	mango	yacht	piano	axe
...
last five					
51*	ostrich	nut	ski	picture	foot
52	titmouse	gourd	skateboard	closet	car
53	emu	olive	wheelbarrow	vase	glass
54	penguin	pickle	surfboard	fan	screwdriver
55	bat	squash	elevator	telephone	shoes

* Since the total number of listed items varied between 50 and 60, the numbers of middle and bottom ranks are not identical with the original ranks for all categories.

Figure 1.3 A selection of examples from Rosch's goodness-of-example rating tests (Rosch 1975)

Frame Semantics

<https://framenet.icsi.berkeley.edu/fndrupal/frameIndex>



Commonsense Data (ConceptNet)

<http://conceptnet5.media.mit.edu/>

knife

knife – CapableOf → spread butter

knife can spread butter

knife – CapableOf → spread peanut butter

A knife can spread peanut butter

knife – UsedFor → stab

knife is for stabbing

knife – AtLocation → in kitchen

Something you might find in a kitchen is a knife.

knife – UsedFor → cut food

knife may be used to cut food.

cut – RelatedTo → knife

cut is related to knife

knife – AtLocation → kitchen drawer

You are likely to find a knife in a kitchen drawer

knife – MadeOf → steel

a knife can be made from steel.

knife – UsedFor → butter

a knife is used for butter

knife – IsA → tool

A knife is a type of tool

knife – AtLocation → kitchen

*Something you find in the kitchen is knife

knife – UsedFor → cut

When you want to cut, you will use knife.

knife – AtLocation → drawer

*Something you find in a drawer is a knife

knife – IsA → weapon

Kinds of weapons : knife

knife – UsedFor → eat

When you want to eat, you will use a knife.

machete – IsA → knife

a machete is a kind of a knife.

knife – AtLocation → store

*Something you find at a store is knives

blade – PartOf → knife

The blade is part of a knife

knife – CapableOf → butter bread

a knife can butter bread

in kitchen – AtLocation → knife

Something you find a knife is in the kitchen.

$$A \sqsubseteq B$$
$$A \sqsubseteq \neg B$$
$$A \sqcap B$$
$$A \sqcup B$$
$$A \equiv B$$
$$\top \sqsubseteq \forall P.A$$
$$\exists / \forall P.A$$

**Ontologies &
Description Logics**

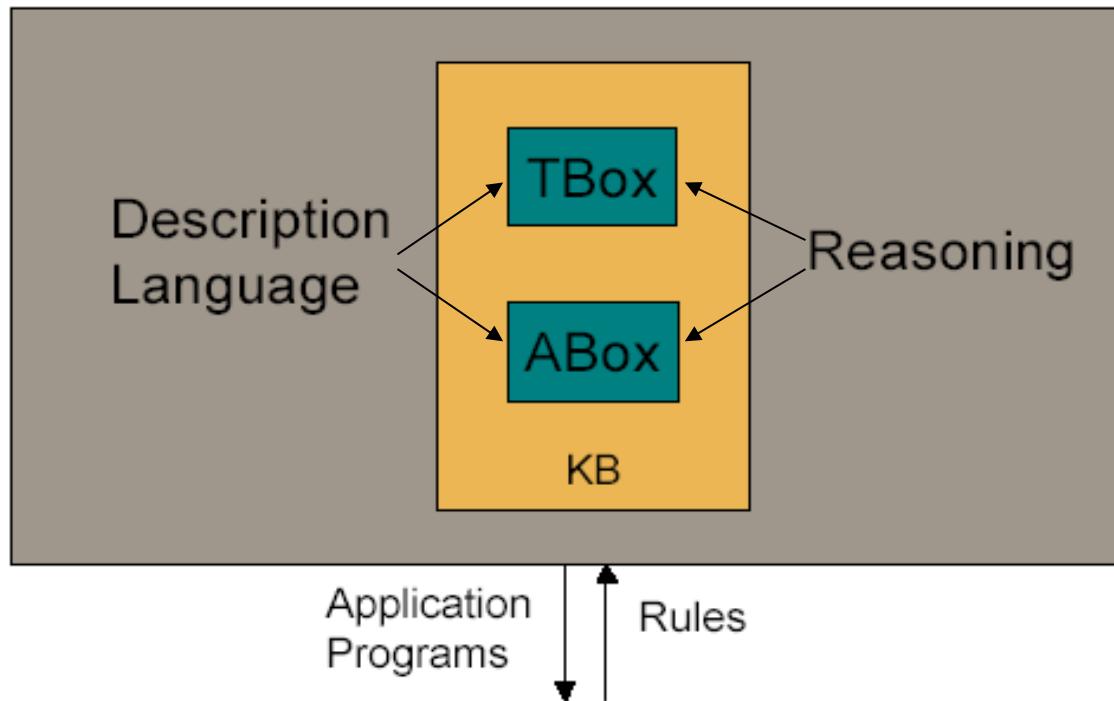
Description Logic

- Description Logics
 - Overcome the ambiguities of early semantic networks and frames
- Well-studied and decidable (most DL languages)
- Tight coupling between theory and practice

TBox and ABox

- TBox: terminology
 - The vocabulary of an application domain:
 - Concepts: sets of individuals
 - Roles: binary relationships between individuals.
 - Examples:
 - Concepts: Person, Female, Mother
 - Role: hasChild, meaning that some person is the child of some other
- ABox: assertions
 - About named individuals in terms of this vocabulary
 - Example
 - Elizabeth and Charles are Persons. We write this as Person(Elizabeth), and Person(Charles).
 - Individuals, like “myCar”, have attributes, like “color”, and those attributes have values, like “red”. When this happens we say that red is the colorOf attribute of myCar.
We write this as colorOf(myCar, red).

Architecture of a DL System

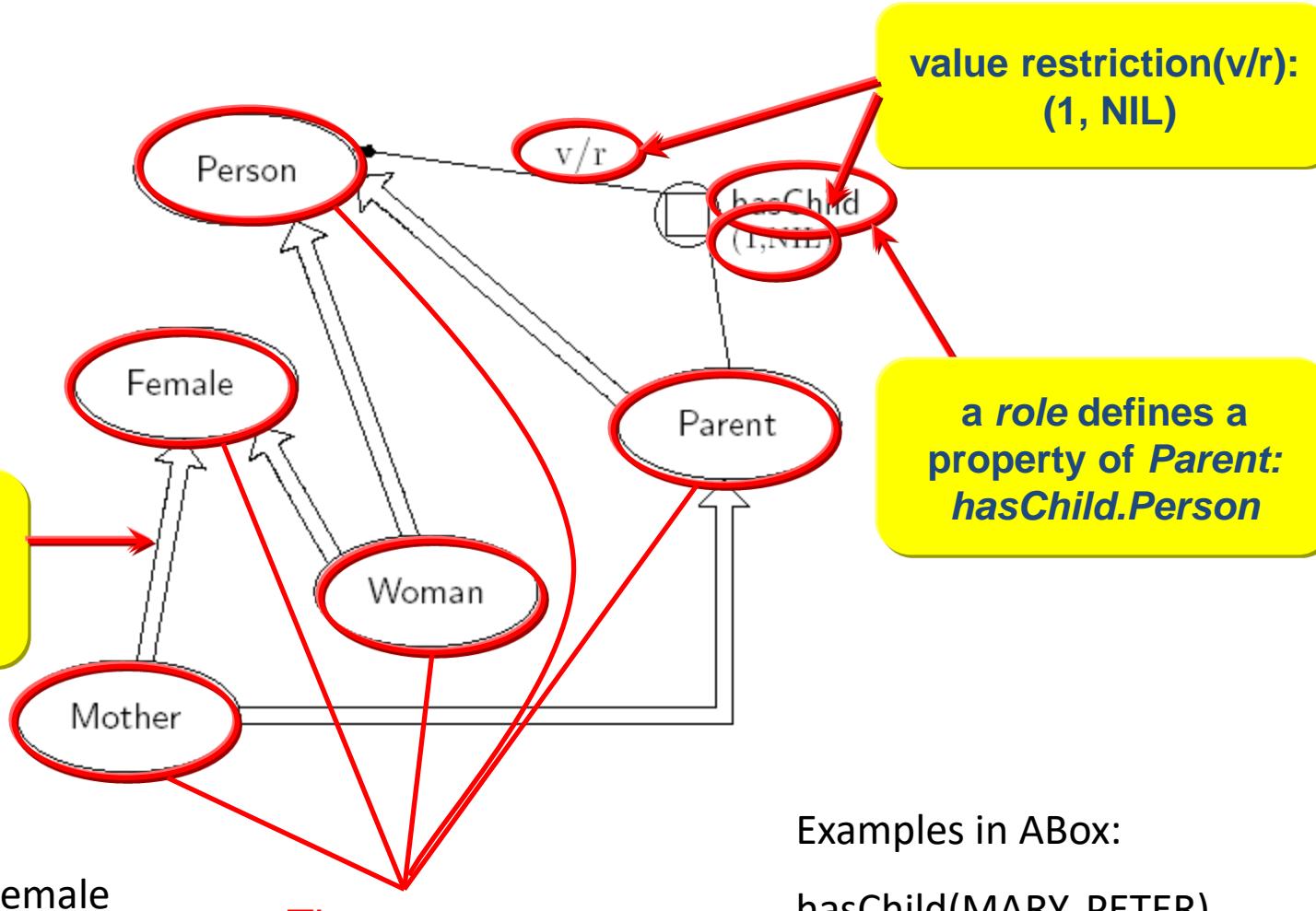


Formulas

- Building blocks that allow complex descriptions of concepts and roles.
 - Example (we'll look at the syntax in more detail soon.)
 - A Woman is a Female Person
 - Woman = Person \sqcup Female
 - A Mother is a Woman and she has a child
 - Mother = Woman \sqcup hasChild.T
- The TBox can be used to assign names to complex descriptions.

*We will use the terms *description* and *concept* interchangeably.*

An Example about Family Relationships



Examples in TBox:

Woman ⊑ Person \sqcup Female

Mother ⊑ Woman \sqcup hasChild.Person

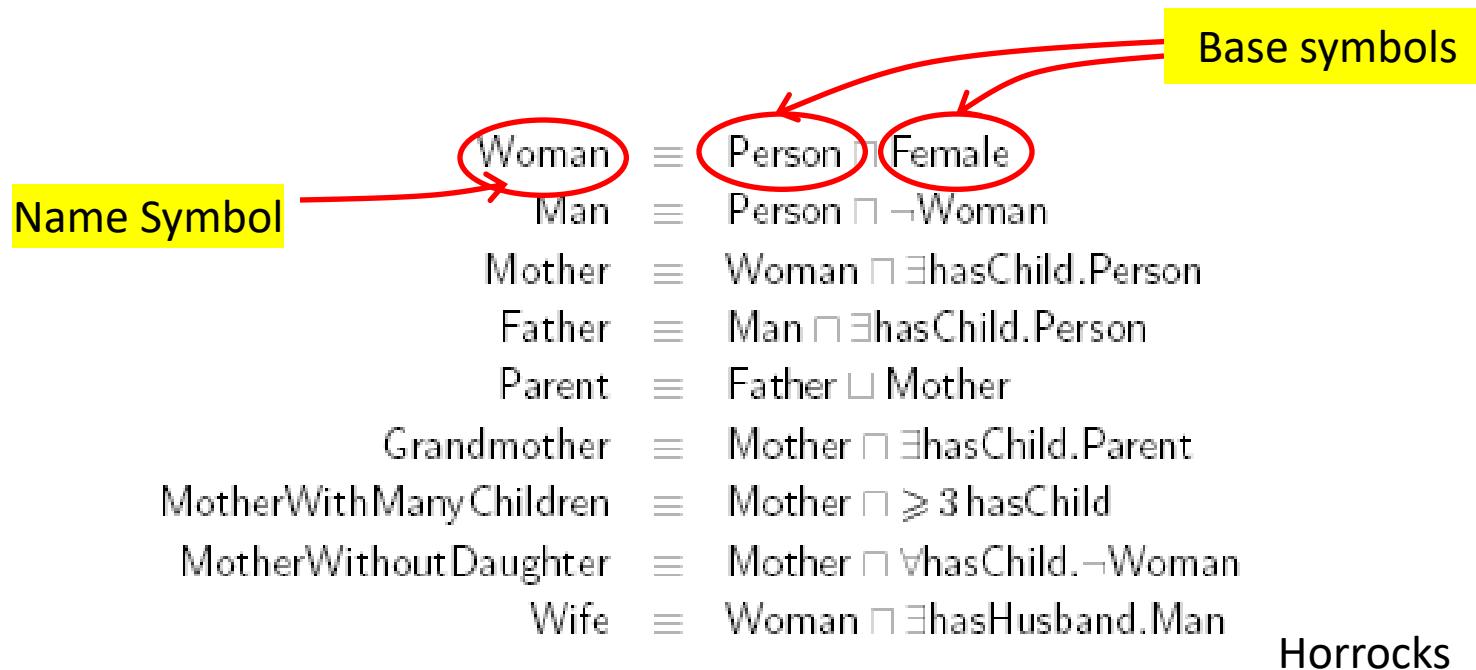
Examples in ABox:

hasChild(MARY, PETER)

Father(PETER)

Name Symbols vs. Base Symbols

- Atomic concepts occurring in a TBox \mathbf{T} can be divided into two sets, name symbols $N_{\mathbf{T}}$ (or defined concepts) and base symbols $B_{\mathbf{T}}$ (or primitive concepts, occur only on the right-hand side)
- A base interpretation for \mathbf{T} only interprets the base symbols.



DL for the Semantic Web

- Web Ontology Language (OWL): W3C Recommendation on 10 Feb 2004
- builds on RDF and RDF Schema and adds more vocabulary for describing properties and classesExtends existing Web standards
- has three increasingly-expressive sublanguages: OWL Lite (based on DL SHIF(D)), OWL DL (based on DL SHOIN(D)), and OWL Full (OWL DL + RDF)
- benefits from many years of DL research
 - Well defined **semantics**
 - **Formal properties** well understood (complexity, decidability)
 - Known **reasoning algorithms**
 - Implemented systems (highly optimised)

OWL Class Constructor

Constructor	DL Syntax	Example	Modal Syntax
intersectionOf	$C_1 \sqcap \dots \sqcap C_n$	Human \sqcap Male	$C_1 \wedge \dots \wedge C_n$
unionOf	$C_1 \sqcup \dots \sqcup C_n$	Doctor \sqcup Lawyer	$C_1 \vee \dots \vee C_n$
complementOf	$\neg C$	\neg Male	$\neg C$
oneOf	$\{x_1\} \sqcup \dots \sqcup \{x_n\}$	{john} \sqcup {mary}	$x_1 \vee \dots \vee x_n$
allValuesFrom	$\forall P.C$	\forall hasChild.Doctor	$[P]C$
someValuesFrom	$\exists P.C$	\exists hasChild.Lawyer	$\langle P \rangle C$
maxCardinality	$\leq n P$	≤ 1 hasChild	$[P]_{n+1}$
minCardinality	$\geq n P$	≥ 2 hasChild	$\langle P \rangle_n$

OWL Axioms

Axiom	DL Syntax	Example
subClassOf	$C_1 \sqsubseteq C_2$	Human \sqsubseteq Animal \sqcap Biped
equivalentClass	$C_1 \equiv C_2$	Man \equiv Human \sqcap Male
disjointWith	$C_1 \sqsubseteq \neg C_2$	Male $\sqsubseteq \neg$ Female
sameIndividualAs	$\{x_1\} \equiv \{x_2\}$	{President_Bush} \equiv {G_W_Bush}
differentFrom	$\{x_1\} \sqsubseteq \neg \{x_2\}$	{john} $\sqsubseteq \neg$ {peter}
subPropertyOf	$P_1 \sqsubseteq P_2$	hasDaughter \sqsubseteq hasChild
equivalentProperty	$P_1 \equiv P_2$	cost \equiv price
inverseOf	$P_1 \equiv P_2^-$	hasChild \equiv hasParent $^-$
transitiveProperty	$P^+ \sqsubseteq P$	ancestor $^+$ \sqsubseteq ancestor
functionalProperty	$T \sqsubseteq \leqslant 1P$	T $\sqsubseteq \leqslant 1$ hasMother
inverseFunctionalProperty	$T \sqsubseteq \leqslant 1P^-$	T $\sqsubseteq \leqslant 1$ hasSSN $^-$

- Axioms (mostly) reducible to inclusion (\sqsubseteq)
 - e.g. $C \sqsubseteq D$ iff both $C \sqsubseteq D$ and $D \sqsubseteq C$

Ontology Editors



The screenshot shows the Protégé 3.2 beta interface for editing an ontology named `pizza.owl`. The main window is divided into several panels:

- SUBCLASS EXPLORER**: Shows the asserted hierarchy of classes. `RealItalianPizza` is selected in the `Pizza` category.
- CLASS EDITOR**: For the class `RealItalianPizza` (instance of `owl:Class`). It includes sections for:
 - Annotations**:

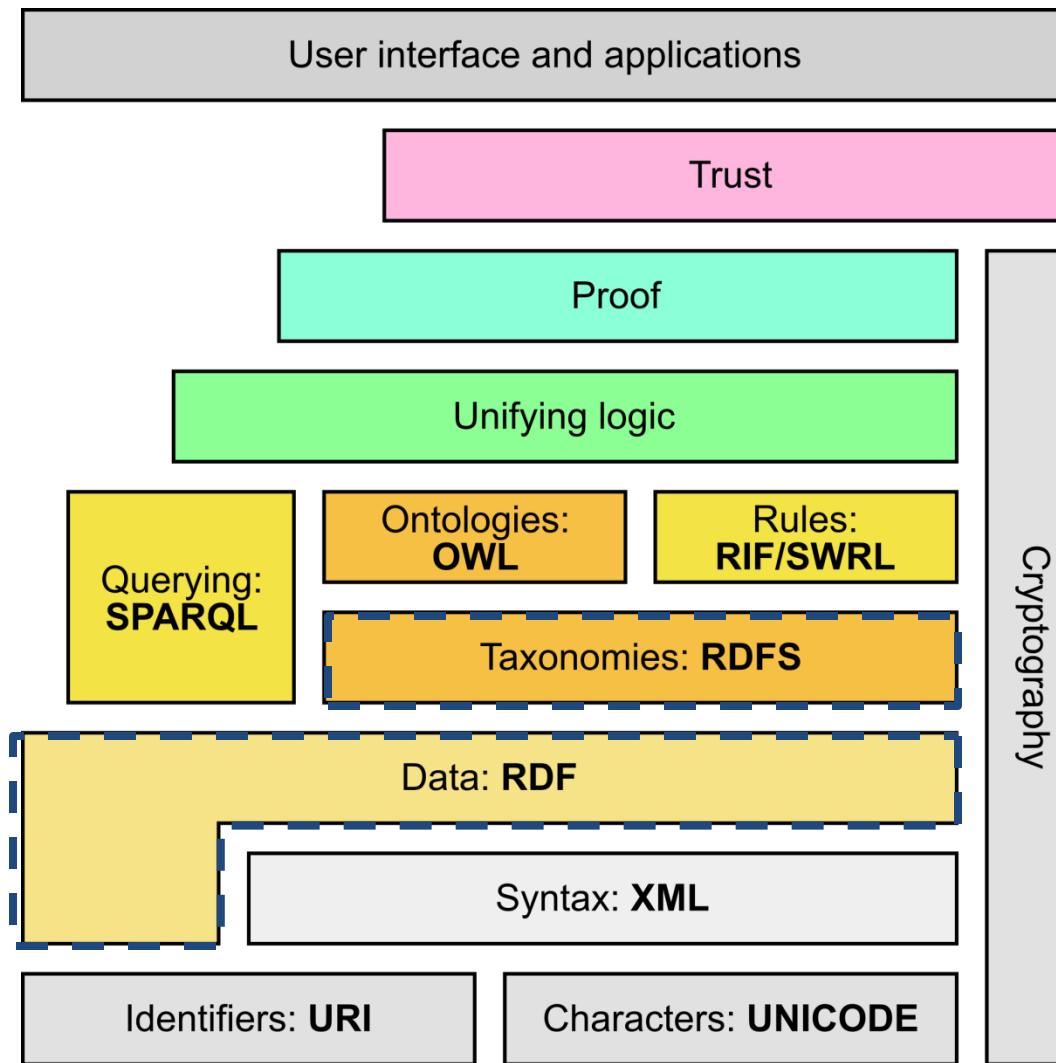
Property	Value	Lang
rdfs:comment	This defined class has conditions that are part of the definition: ie any Pizza that has the country of origin, Italy is a RealItalianPizza. It also has conditions that merely describe the members - that all RealItalianPizzas must only have ThinAndCrispy bases.	en
rdfs:label	PizzaitalianaReal	pt
 - Asserted Conditions**:
 - `Pizza` `hasCountryOfOrigin` `has Italy` (NECESSARY & SUFFICIENT)
 - `hasBase` `only` `ThinAndCrispyBase` (NECESSARY)
 - `hasBase` `some` `PizzaBase` (INHERITED [from Pizza])
 - Disjoints**: An empty panel.

At the bottom, there are tabs for `Logic View` and `Properties View`.



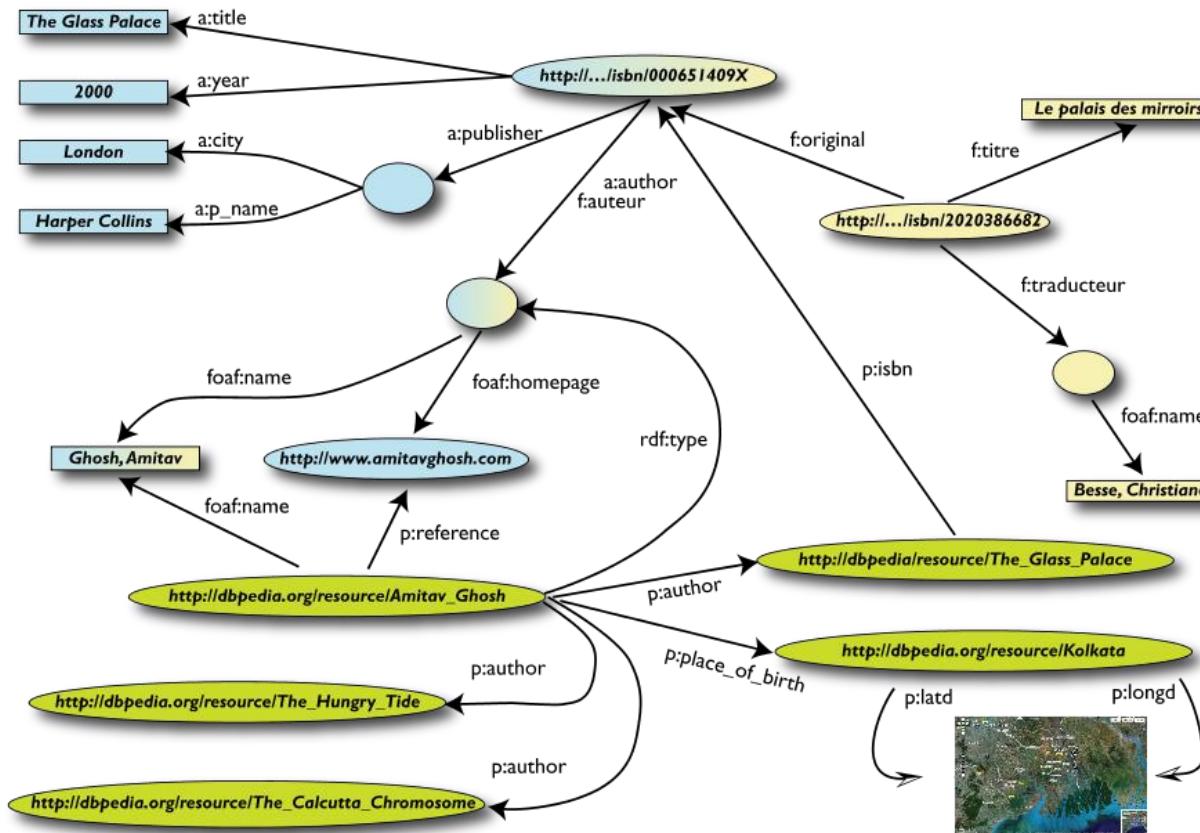
Semantic Web

Semantic Web Stack



RDF: a Direct Connected Graph based Model

- Different interconnected triples lead to a more complex graphic model.
- Basically a RDF document is a direct connect graph.



RDF Basics

- RDF is a language that enable to describe making statements on resources
 - John is father of Bill
- Statement (or triple) as a logical formula $P(x, y)$, where the binary predicate P relates the object x to the object y
- Triple data model:
`<subject, predicate, object>`
 - **Subject:** Resource or blank node
 - **Predicate:** Property
 - **Object:** Resource (or collection of resources), literal or blank node
- Example:
`<ex:john, ex:father-of, ex:bill>`
- RDF offers only binary predicates (properties)

RDF Vocabulary Description Language

- We need a language for defining RDF types:
 - Define classes:
 - “*#Student* is a class”
 - Relationships between classes:
 - “*#Student* is a sub-class of *#Person*”
 - Properties of classes:
 - “*#Person* has a property *hasName*”
- RDF Schema is such a language

RDF Vocabulary Description Language

- Classes:
`<#Student, rdf:type, #rdfs:Class>`
- Class hierarchies:
`<#Student, rdfs:subClassOf, #Person>`
- Properties:
`<#hasName, rdf:type, rdf:Property>`
- Property hierarchies:
`<#hasMother, rdfs:subPropertyOf, #hasParent>`
- Associating properties with classes (a):
 - “The property `#hasName` only applies to `#Person`”
`<#hasName, rdfs:domain, #Person>`
- Associating properties with classes (b):
 - “The type of the property `#hasName` is `#xsd:string`”
`<#hasName, rdfs:range, xsd:string>`

RDFS Vocabulary

- RDFS extends the RDF vocabulary

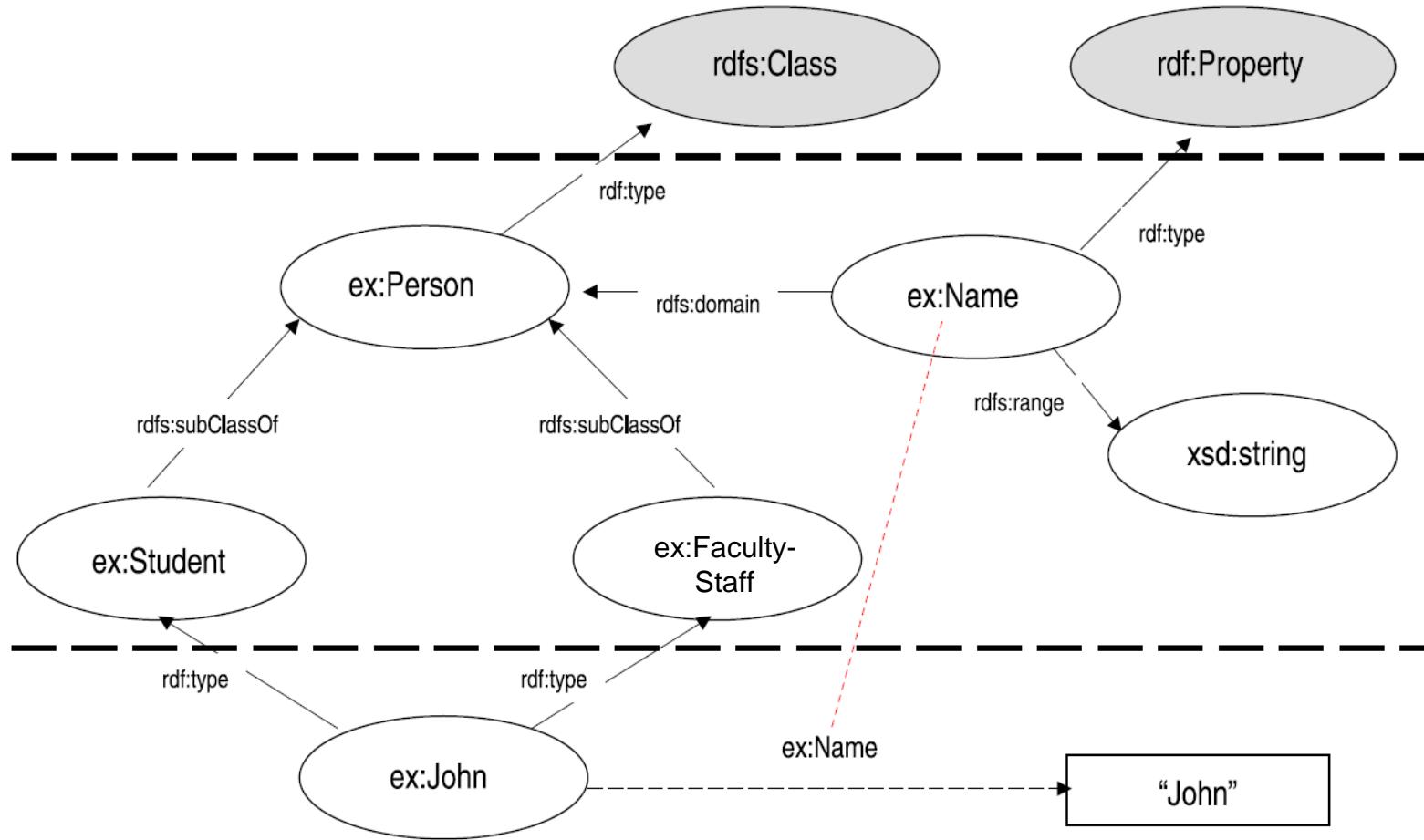
RDFS Classes

- `rdfs:Resource`
- `rdfs:Class`
- `rdfs:Literal`
- `rdfs:Datatype`
- `rdfs:Container`
- `rdfs:ContainerMembershipProperty`

RDFS Properties

- `rdfs:domain`
- `rdfs:range`
- `rdfs:subPropertyOf`
- `rdfs:subClassOf`
- `rdfs:member`
- `rdfs:seeAlso`
- `rdfs:isDefinedBy`
- `rdfs:comment`
- `rdfs:label`

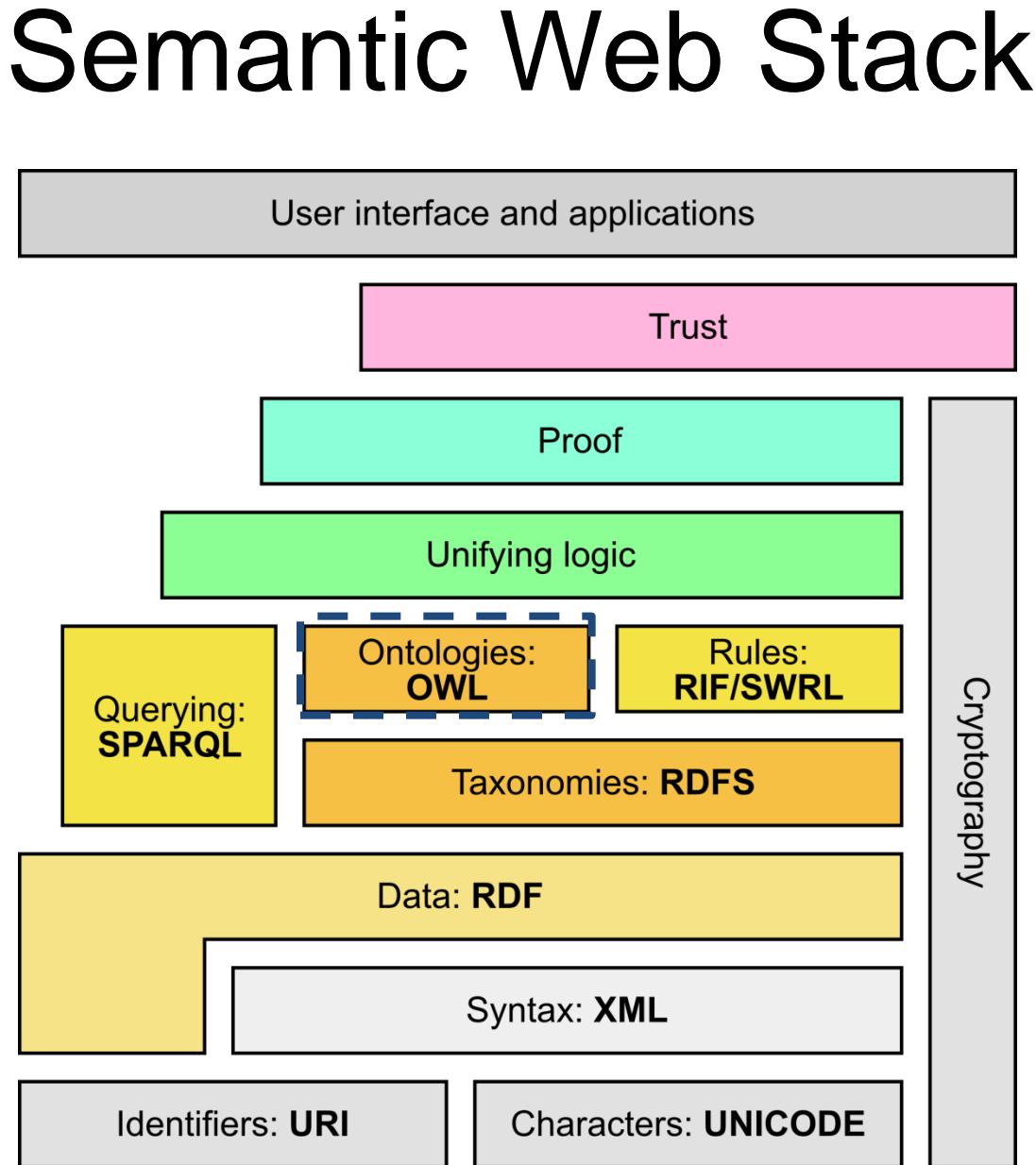
RDFS Example



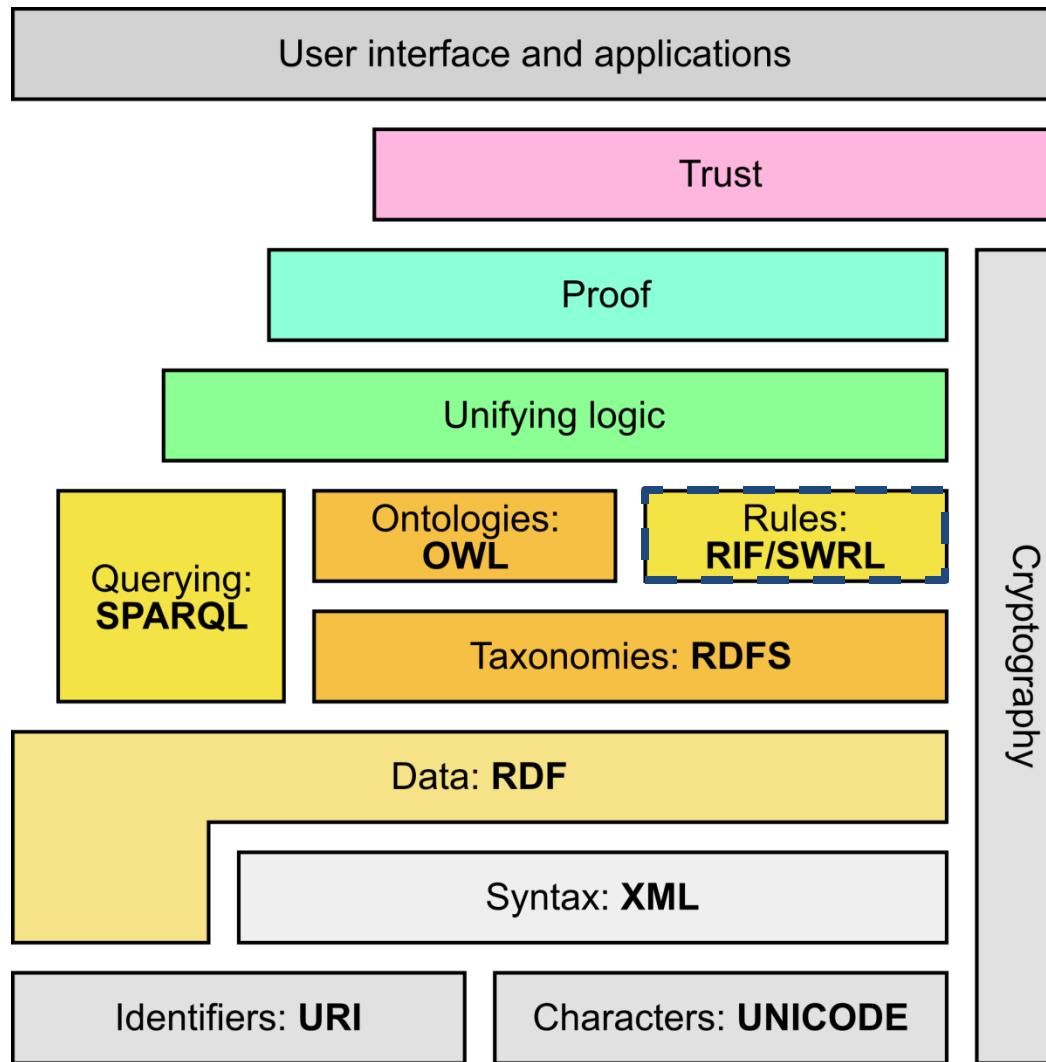
Vocabulary Layer

RDFS Layer

RDF Layer



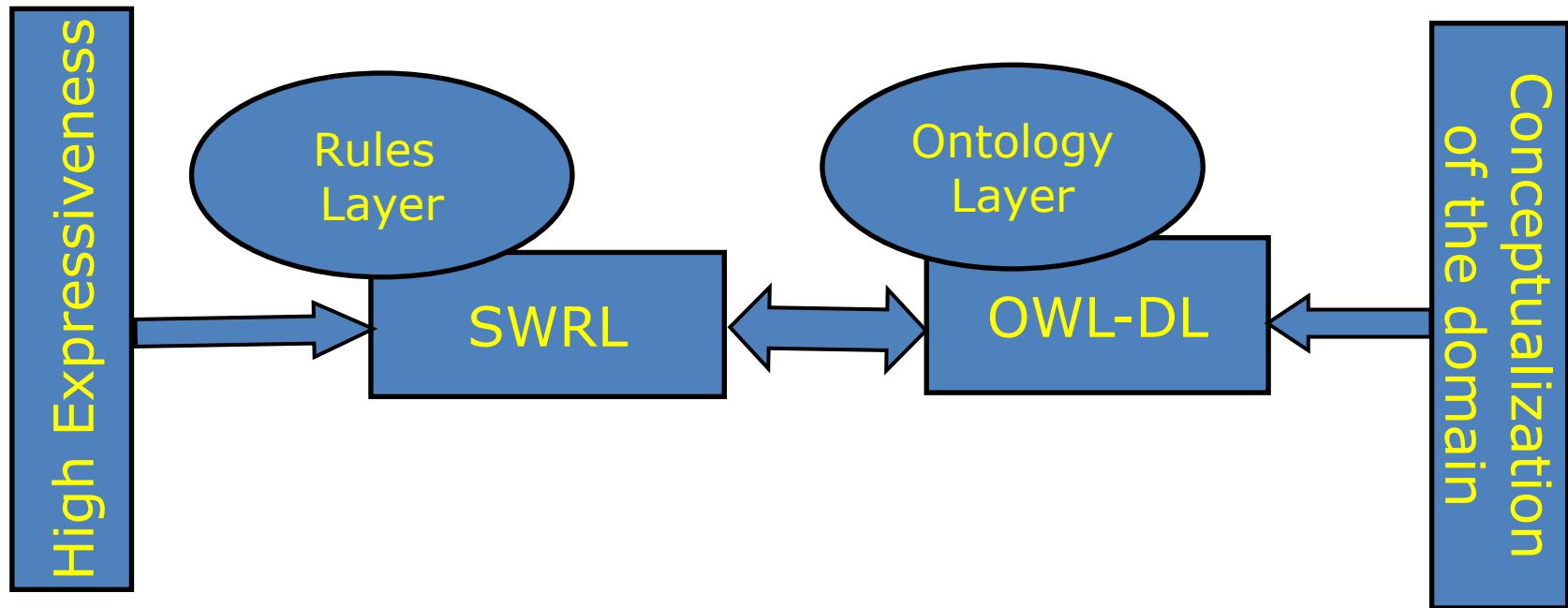
Semantic Web Stack



Adapted from http://en.wikipedia.org/wiki/Semantic_Web_Stack

What is SWRL?

Ontology languages do not offer the expressiveness we want → Rules do it well.



SWRL Rule

An atom is an expression of the form: ***P(arg1 arg2,...)***

- **P** is a predicate symbol (classes, properties...)
- Arguments of the expression: ***arg1, arg2,...*** (individuals, data values or variables)

Example SWRL Rule:

Person(?p) ^ hasSibling(?p,?s) ^ Man(?s) → hasBrother(?p,?s)

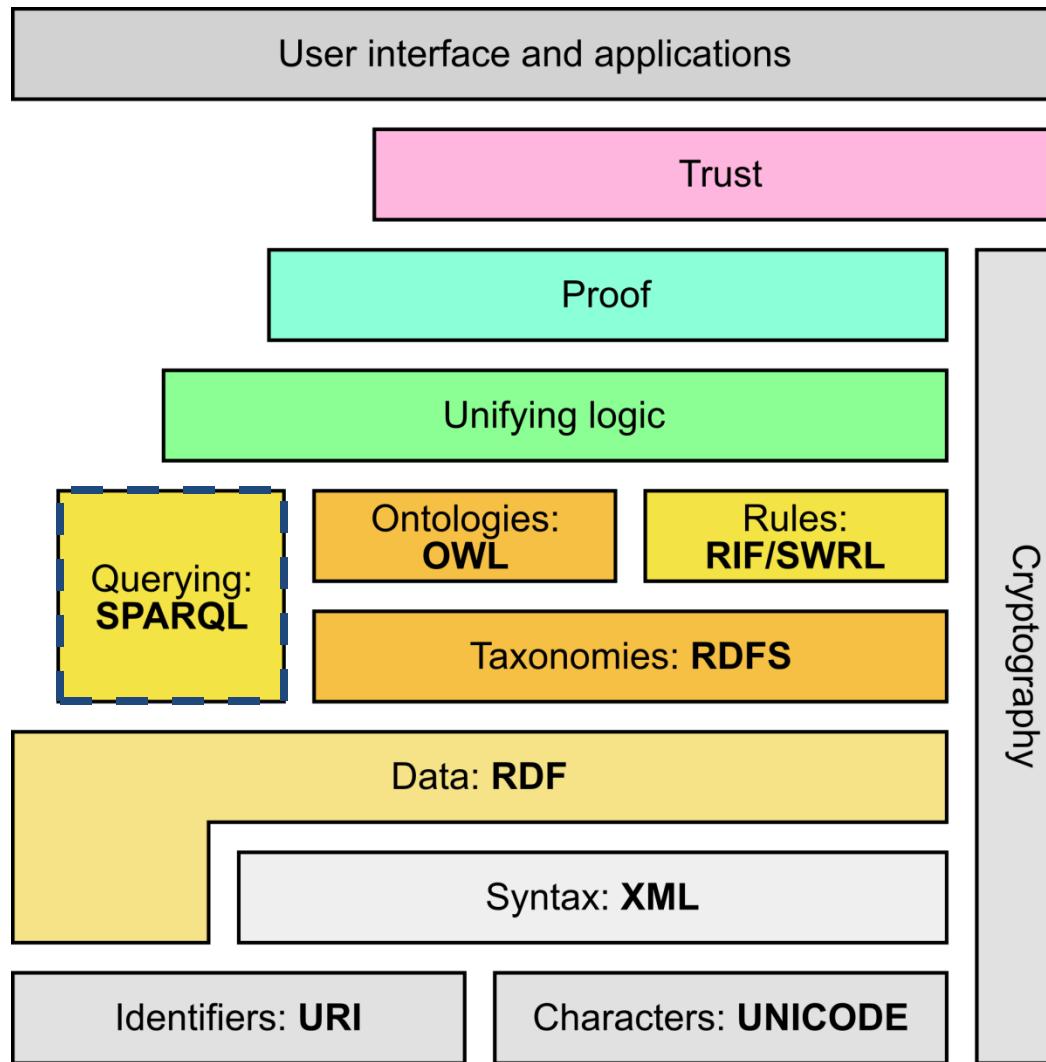


antecedent



consequent

Semantic Web Stack



Adapted from http://en.wikipedia.org/wiki/Semantic_Web_Stack

SPARQL

- Query Language for RDF.

Find all DrugBank drugs along with dosage and disease indication information.

PREFIX rdfs: <<http://www.w3.org/2000/01/rdf-schema#>>

PREFIX db: <http://bio2rdf.org/drugbank_vocabulary:>

SELECT

?drug_name ?dosage ?indication

WHERE {

?drug a db:Drug .

?drug rdfs:label ?drug_name .

OPTIONAL { ?drug db:dosage ?dosage . }

OPTIONAL { ?drug db:indication ?indication . }

}

SPARQL (Yes/No Query)

Is the Amazon river longer than the Nile River?

```
PREFIX prop: <http://dbpedia.org/property/>
ASK {
    <http://dbpedia.org/resource/Amazon_River> prop:length ?amazon .
    <http://dbpedia.org/resource/Nile> prop:length ?nile .
    FILTER(?amazon > ?nile) .
}
```

http://dbpedia.org/sparql

The screenshot shows a web-based SPARQL query editor. At the top, there is a header bar with navigation icons (back, forward, search) and a URL field containing "de.dbpedia.org/sparql". Below the header is a blue title bar labeled "Virtuoso SPARQL Query Editor". The main area has two sections: "Default Data Set Name (Graph IRI)" with an empty input field, and "Query Text" containing the following SPARQL query:

```
PREFIX prop: <http://dbpedia.org/property/>
ASK
{
  <http://dbpedia.org/resource/Amazon_River> prop:length ?amazon .
  <http://dbpedia.org/resource/Nile> prop:length ?nile .
  FILTER(?amazon > ?nile)
}
```

APIs

- Helpful for building AI applications.
- Typical Support:
 - A RDF API
 - Serialization: Reading and writing RDF in RDF/XML, N3 and N-Triples
 - An OWL API
 - In-memory and persistent storage
 - SPARQL query engine

Recommended Reading

1

Frames, Concepts, and Conceptual Fields

Lawrence W. Barsalou
University of Chicago

http://barsaloulab.org/Online_Articles/1992-Barsalou-chap-frames.pdf

Recommended Reading

Intelligent Machines

An AI with 30 Years' Worth of Knowledge Finally Goes to Work

An effort to encode the world's knowledge in a huge database has sometimes seemed impractical, but those behind the technology say it is finally ready.

by Will Knight March 14, 2016

Having spent the past 31 years memorizing an astonishing collection of general knowledge, the artificial-intelligence engine created by Doug Lenat is finally ready to go to work.

Lenat's creation is **Cyc**, a knowledge base of semantic information designed to give computers some understanding of how things work in the real world.

<https://www.technologyreview.com/s/600984/an-ai-with-30-years-worth-of-knowledge-finally-goes-to-work/>