Symbolic AI

Andre Freitas

Photo by Vasilyev Alexandr

Today

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

LINKQ

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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
Boeing Co

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

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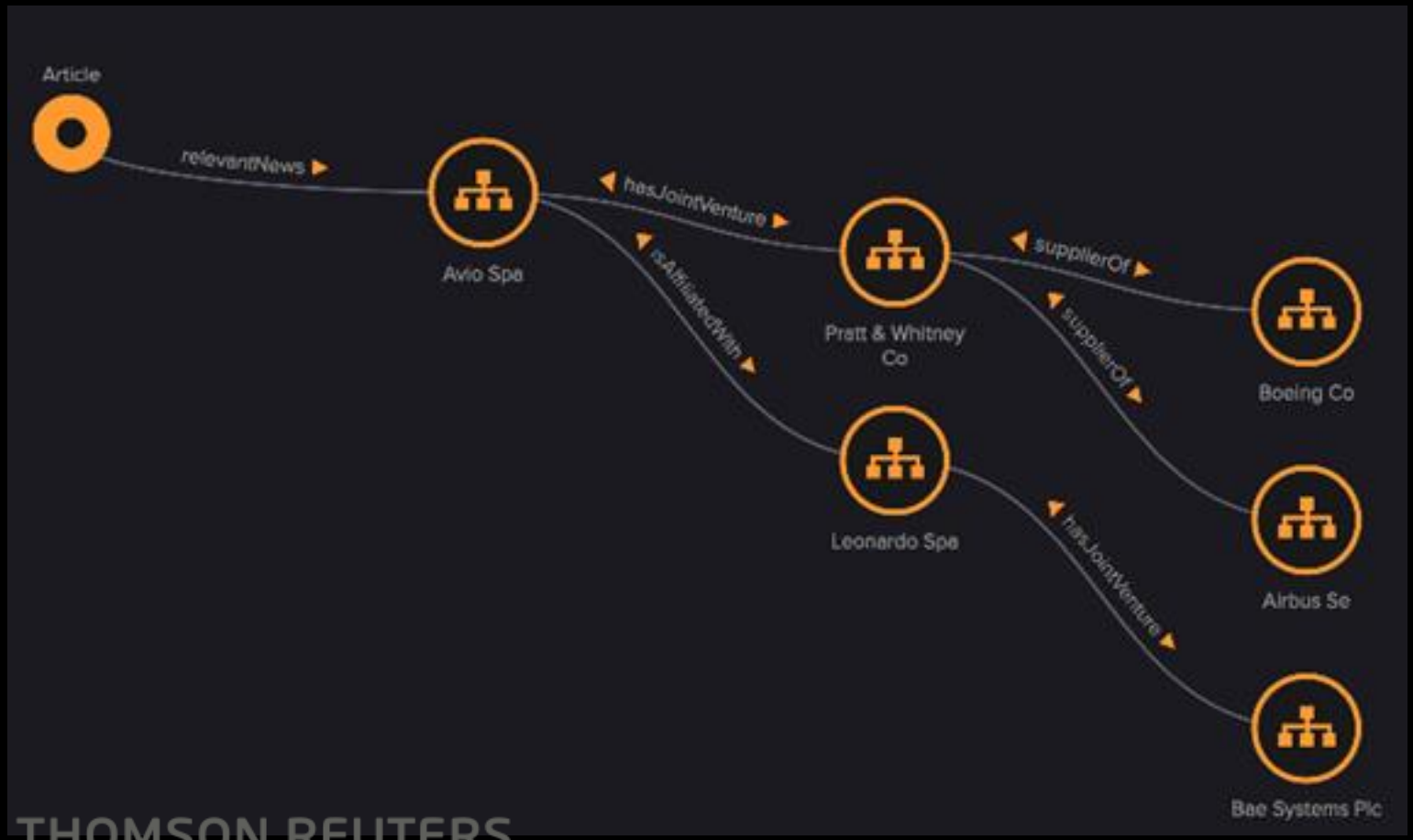
BRIEF-Avio receives EUR 40 mln financing from European Investment Bank <SPA2.MI>

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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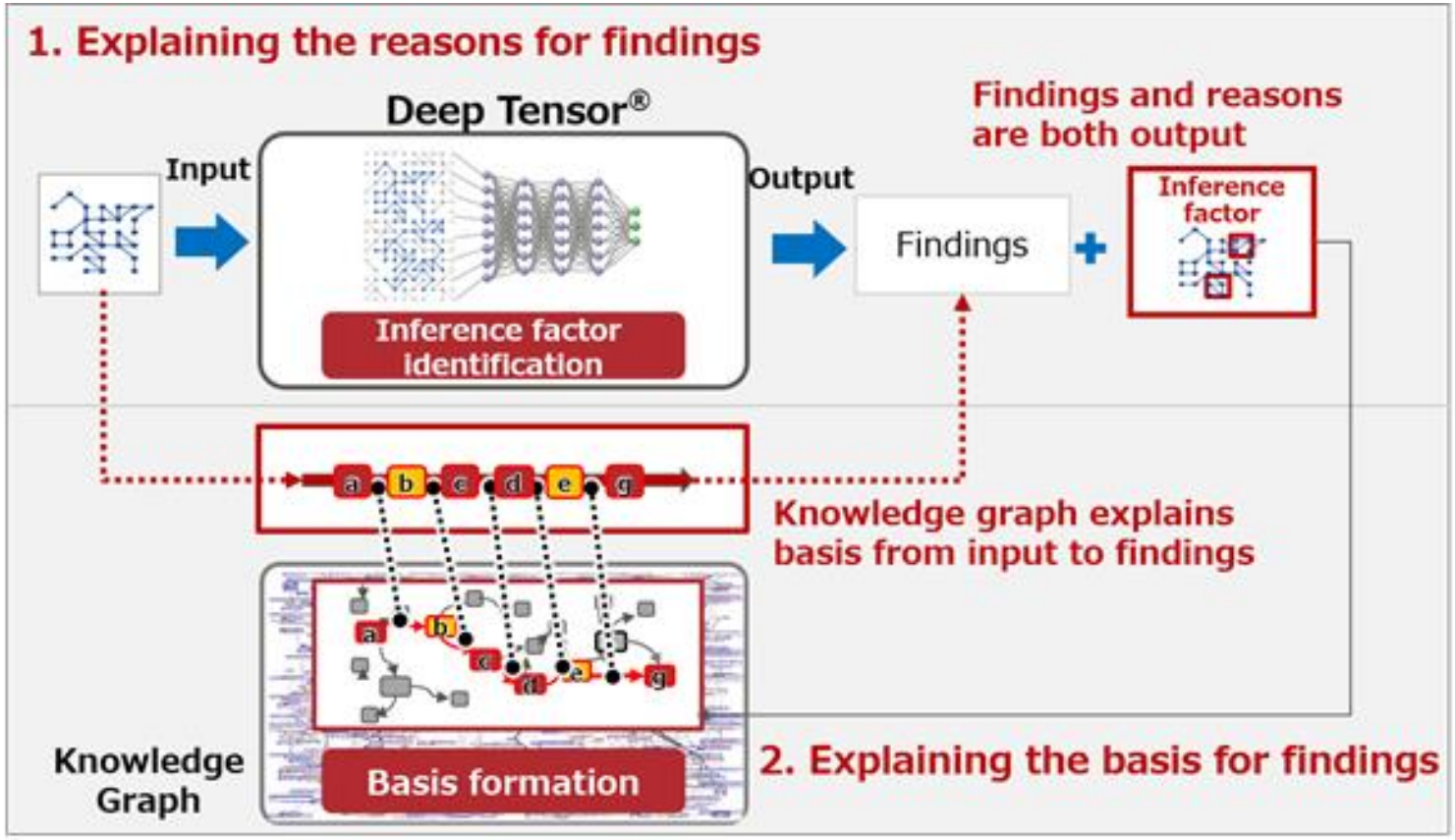
Explainable Findings

From Tensor Inferences Back to KGs



FUJITSU

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-capacitators?
European politicians mentioned in Panama Leaks?

Representation

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

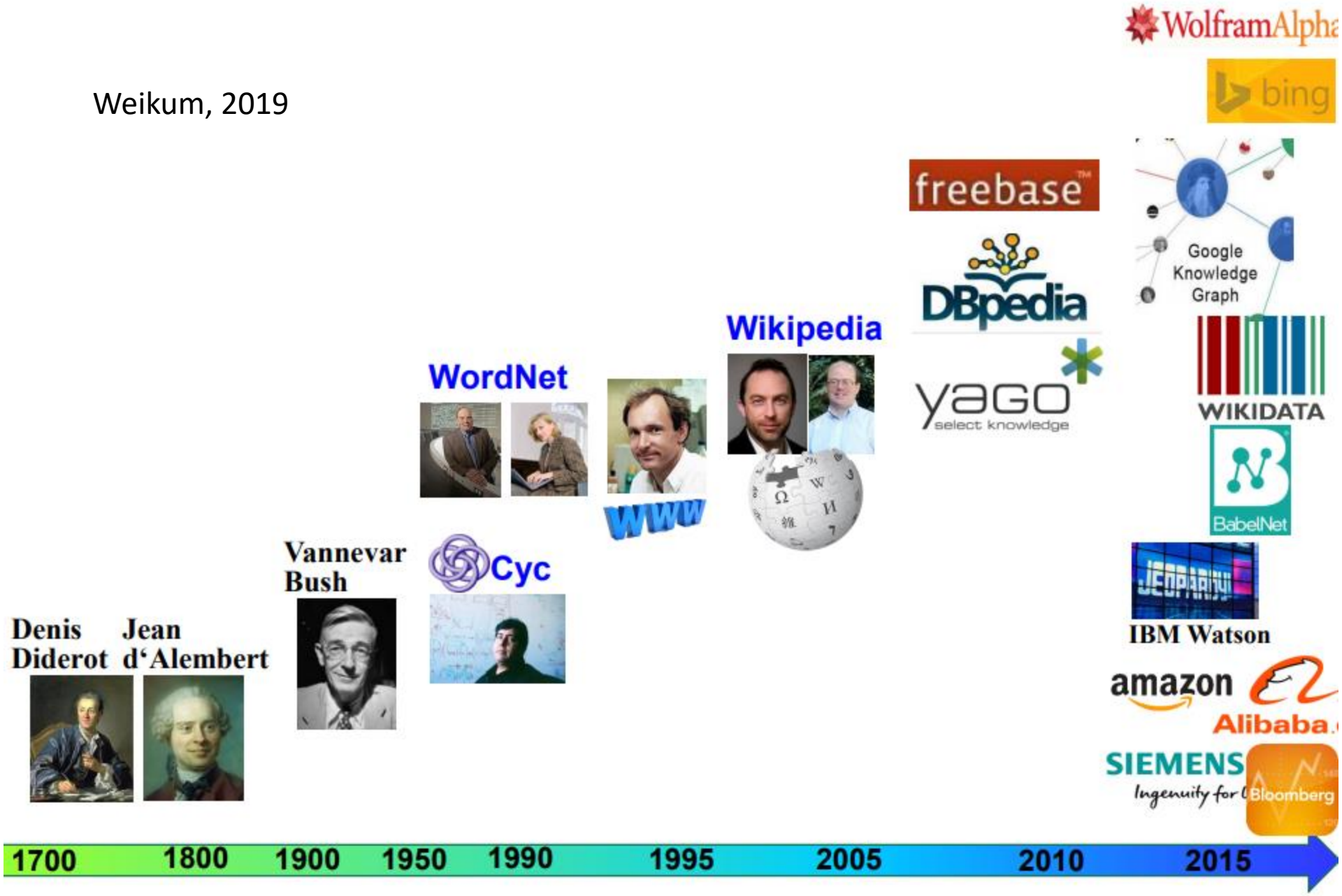
Good Knowledge Representation Languages

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

Knowledge Graphs

Brief History of Knowledge Bases

Weikum, 2019



Terminology

- <u>Ontology</u>
  - provides more complete definitions for concepts
  - Graphical conceptual model
- <u>Thesaurus</u>
  - simple relationships between words
    - synonyms, homonyms, antonyms, etc.
  - often combined with a taxonomy
- <u>Taxonomy</u>
  - hierarchical arrangement of concepts
  - often used as a “backbone” for an ontology
- <u>Lexicon</u>
  - 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 <u>senses</u>

- 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

- <u>Sense</u> (or <u>word sense</u>)
  - 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 <u>polysemous</u> 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 <u>in some or all contexts</u>:
  - couch / sofa
  - big / large
  - automobile / car
  - vomit / throw up
  - Water / H_20

- 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 <u>with respect to one feature of meaning</u>.

- 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 <u>hyponym</u> 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 <u>hypernym/superordinate</u> ("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 <u>IS-A hierarchy</u>:
  - A IS-A B (or A ISA B)
  - B **subsumes** A

Hyponyms and Instances

- WordNet has both <u>classes</u> and <u>instances</u>.

- An <u>instance</u> 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 <u>synset</u> (synonym set), the set of near-synonyms, instantiates a sense or concept, with a <u>gloss</u>.

- Example: chump as a noun with the gloss:

  “a person who is gullible and easy to take advantage of”

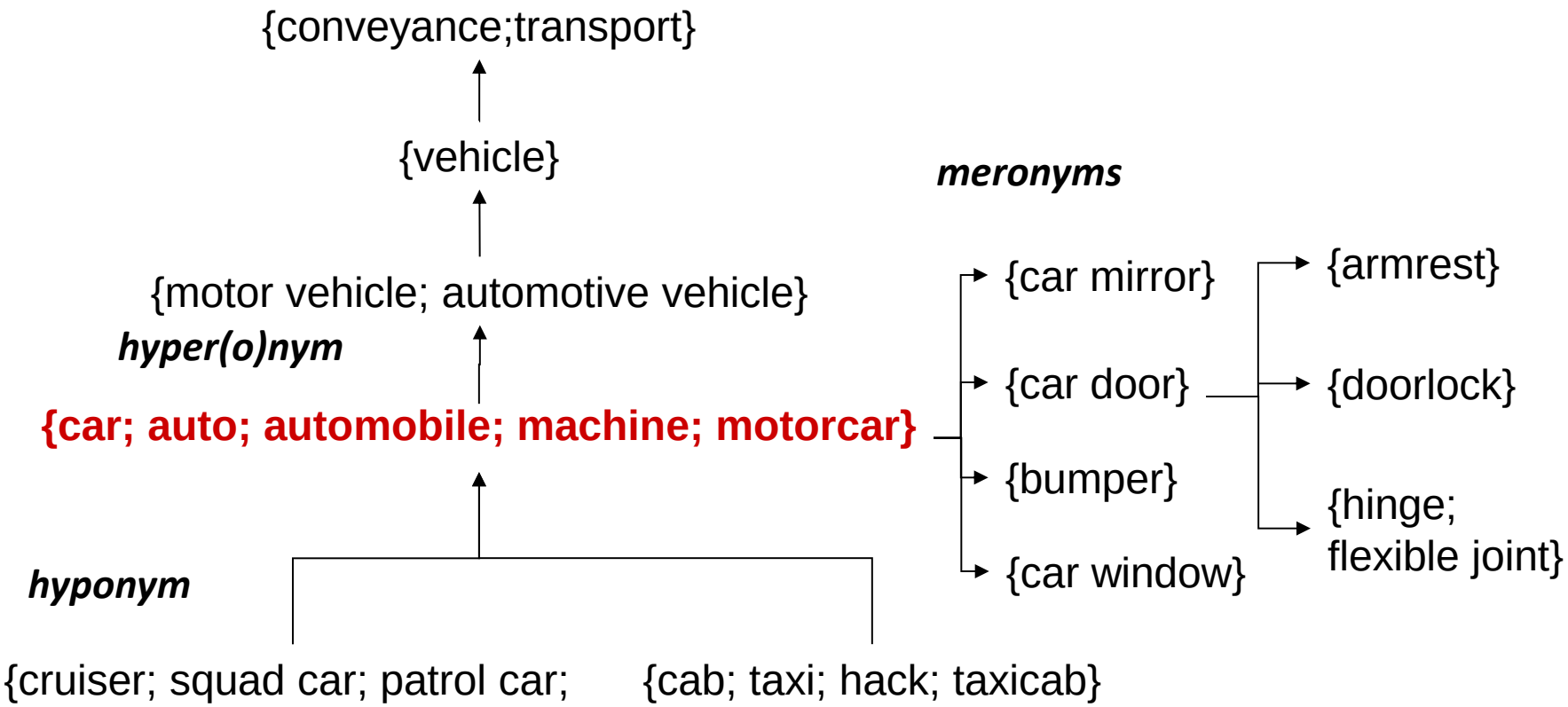
- This sense of “chump” is shared by 9 words:

  chump^{1}, fool^{2}, gull^{1}, mark^{9}, patsy^{1}, fall guy^{1}, sucker^{1}, soft touch^{1}, mug^{2}

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



Hyponymy and meronymy relations are:

- transitive
- directed

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	*to*
2.	CD	Cardinal number	26.	UH	Interjection
3.	DT	Determiner	27.	VB	Verb, base form
4.	EX	Existential *there*	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	*wh*-determiner
10.	LS	List item marker	34.	WP	*wh*-pronoun
11.	MD	Modal	35.	WP$	Possessive *wh*-pronoun
12.	NN	Noun, singular or mass	36.	WRB	*wh*-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

http://wenhoujx.blogspot.com/2013/06/penn-treebank-pos-tags.html

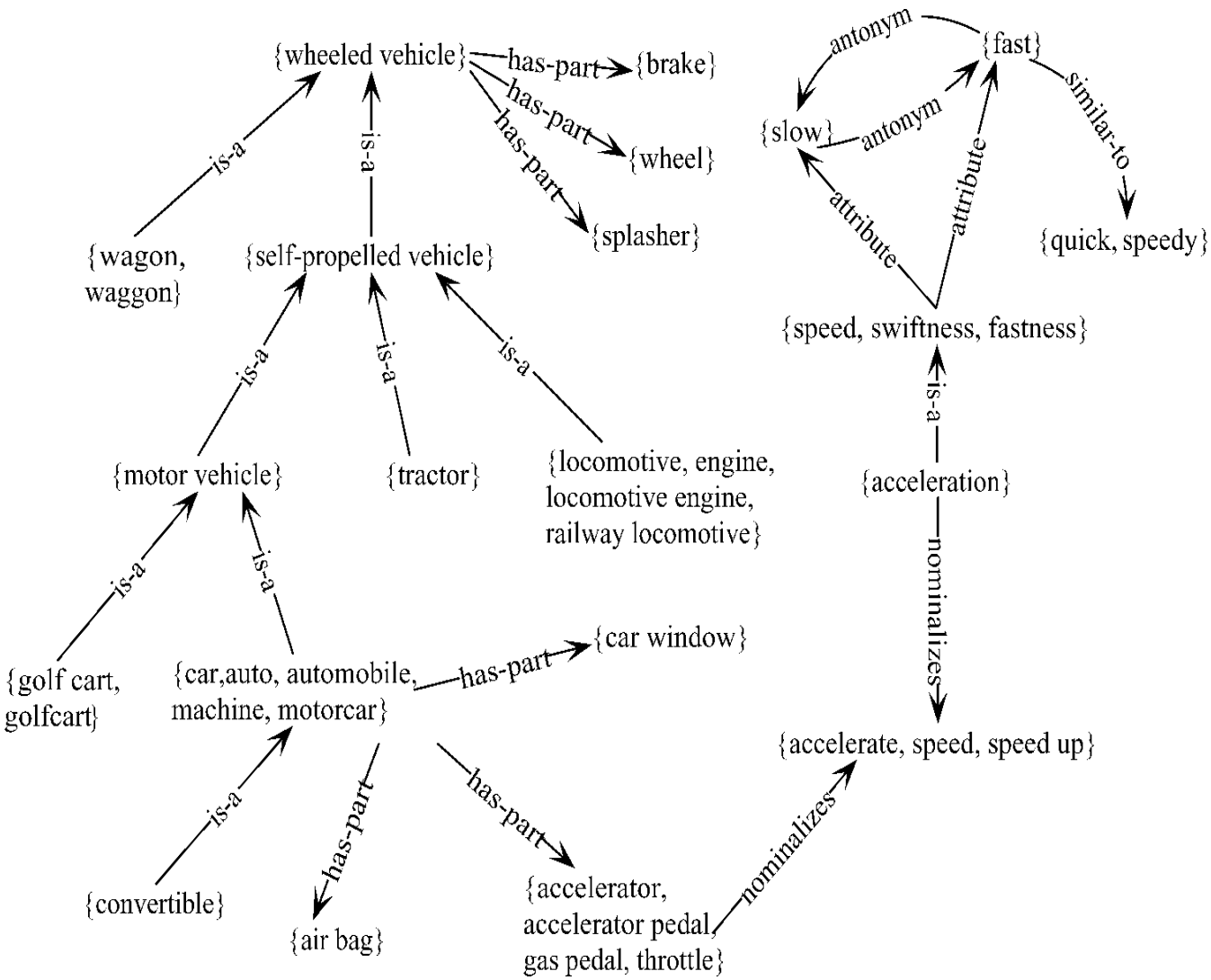
WordNet Noun Relations (Reference)

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

WordNet Verb Relations (Reference)

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

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>
```

Accessing WordNet from Prolog

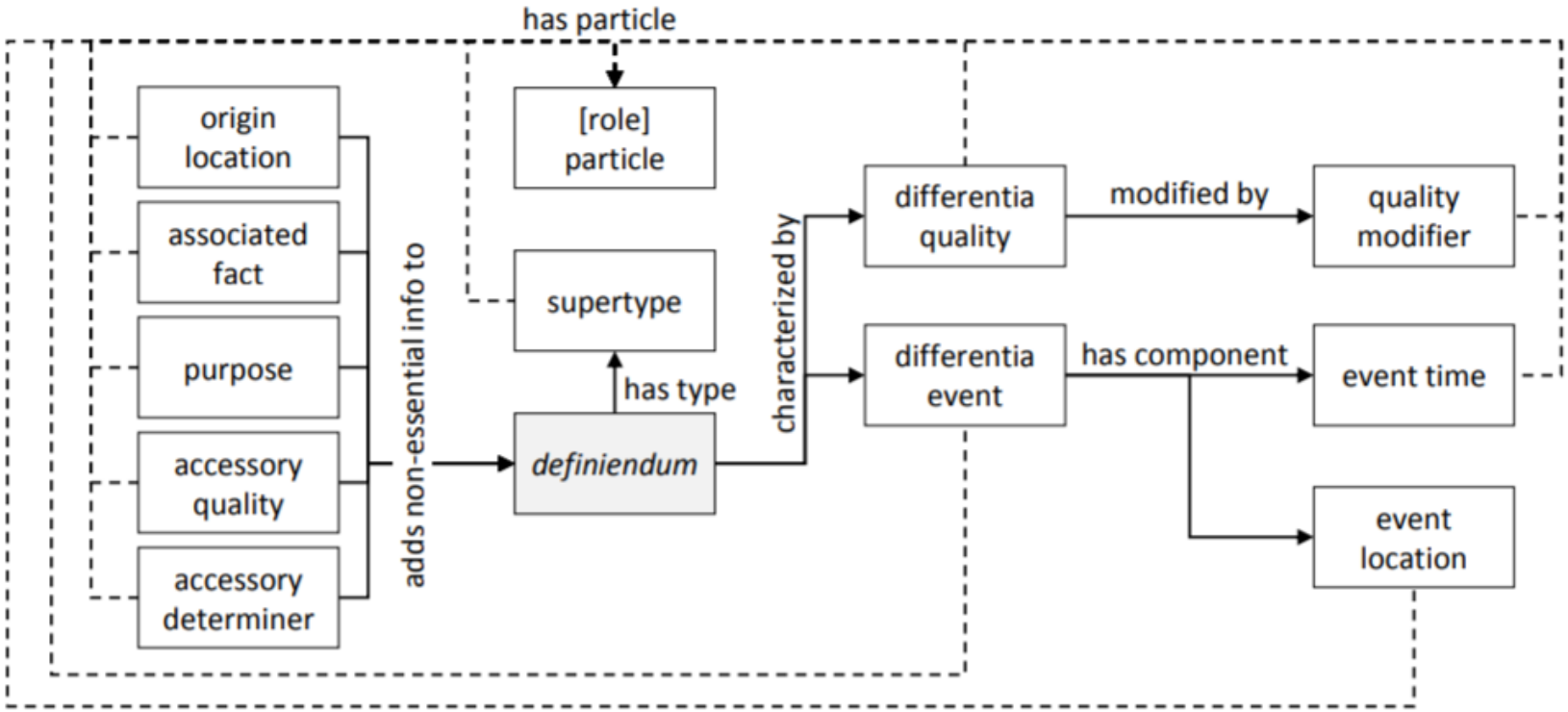
```
? - substance_of(water,X).
        X = [tear|_G407]
? - has_substance(water,X).
        X = [h2o|_G407]

?- part_of(leg,X).
X = [table|_G407]
?- has_part(leg,X).
X = [knee|_G407]
```

https://github.com/ekaf/wordnet-prolog

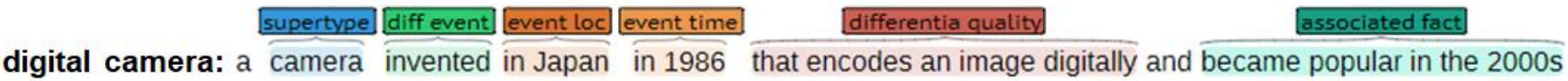
Sarah Witzig

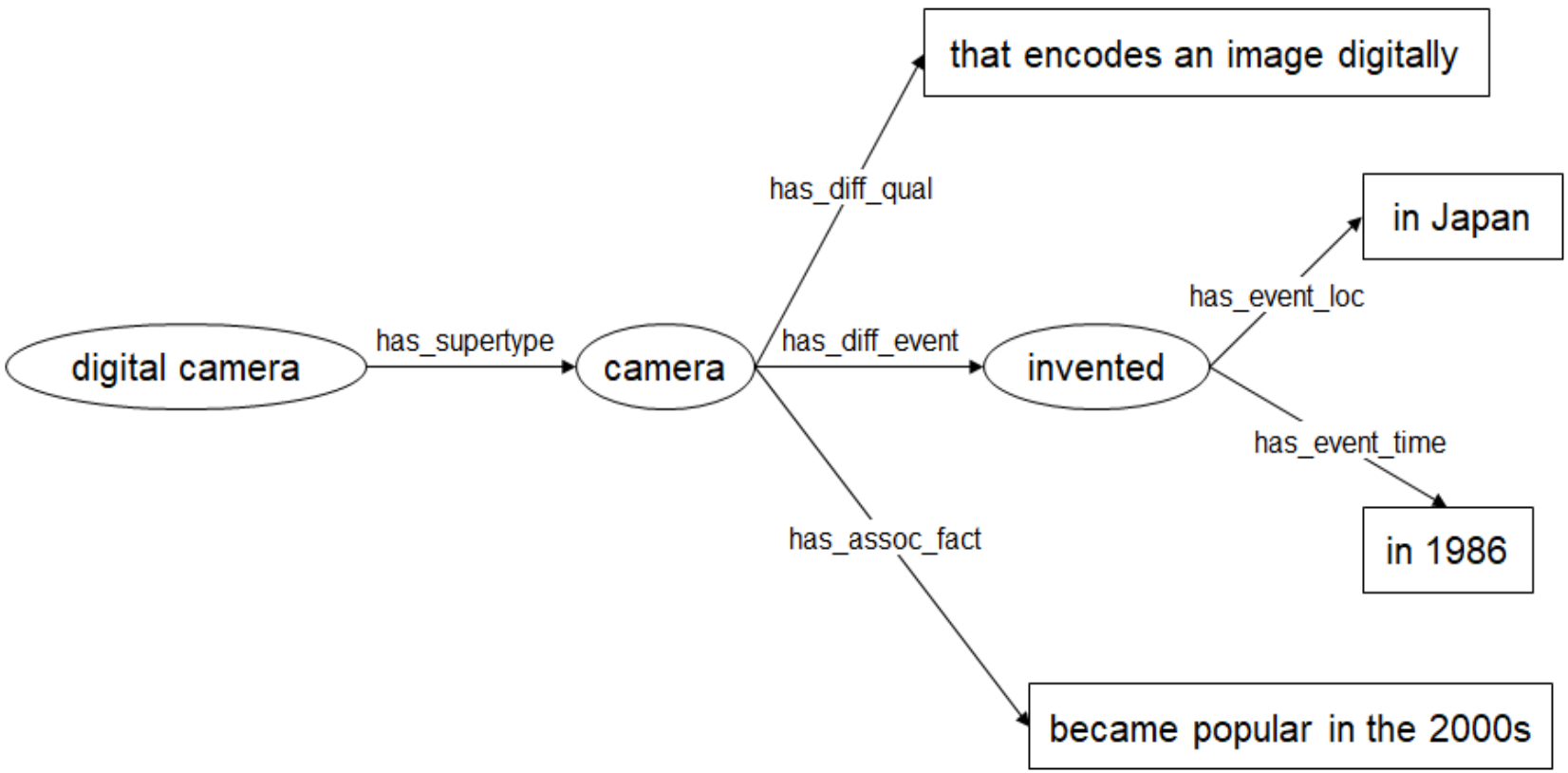
Semantic Roles for Lexical Definitions

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





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

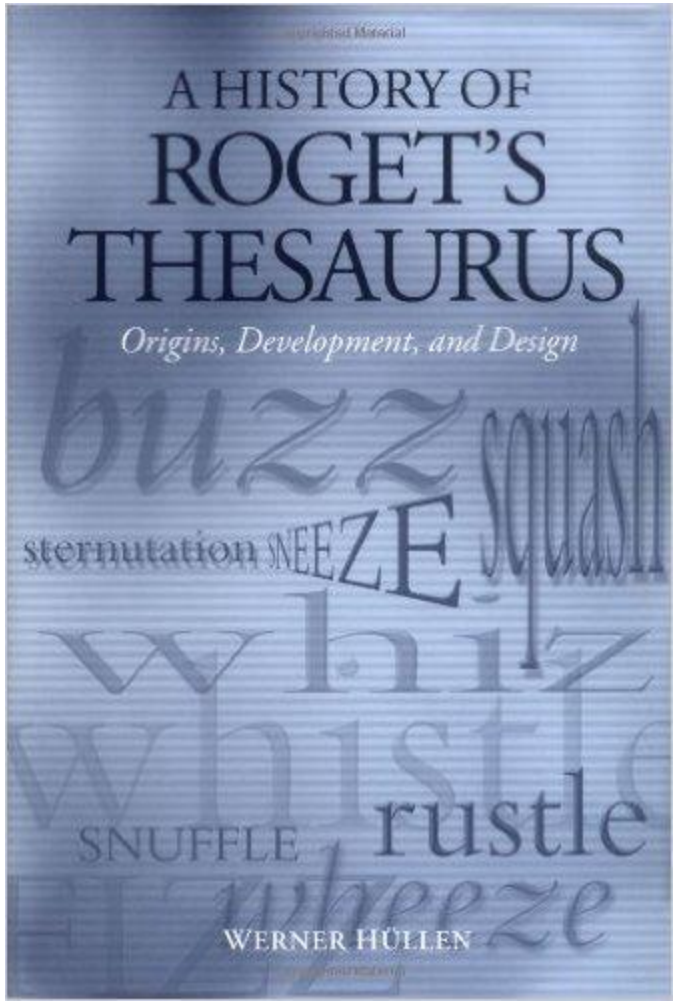
  Definition: The oxygen-carrying proteins of ERYTHROCYTES. They are found in all vertebrates and some invertebrates. The number of globin subunits in the hemoglobin quaternary structure differs between species. Structures range from monomeric to a variety of multimeric arrangements

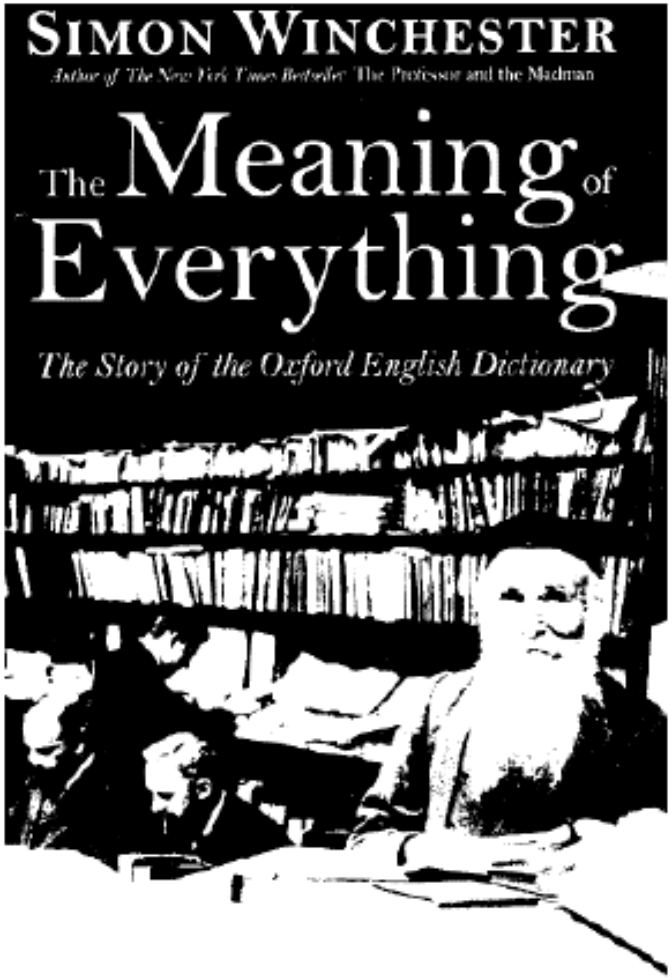
The MeSH Hierarchy

1. + Anatomy [A]
2. + Organisms [B]
3. + Diseases [C]
4. − Chemicals and Drugs [D]
   - Inorganic Chemicals [D01] +
   - Organic Chemicals [D02] +
   - Heterocyclic Compounds [D03] +
   - Polycyclic Compounds [D04] +
   - Macromolecular Substances [D05] +
   - Hormones, Hormone Substitutes, and
   - Enzymes and Coenzymes [D08] +
   - Carbohydrates [D09] +
   - Lipids [D10] +
   - Amino Acids, Peptides, and Proteins [
   - Nucleic Acids, Nucleotides, and Nuclec
   - Complex Mixtures [D20] +
   - Biological Factors [D23] +
   - Biomedical and Dental Materials [D25
   - Pharmaceutical Preparations [D26] +
   - 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]
      - Erythrocruorins [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.

- <u>Componential analysis</u> or <u>semantic decomposition</u> approach:
  - word meaning is modelled in terms of <u>semantic features</u> or <u>primitives</u>.

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

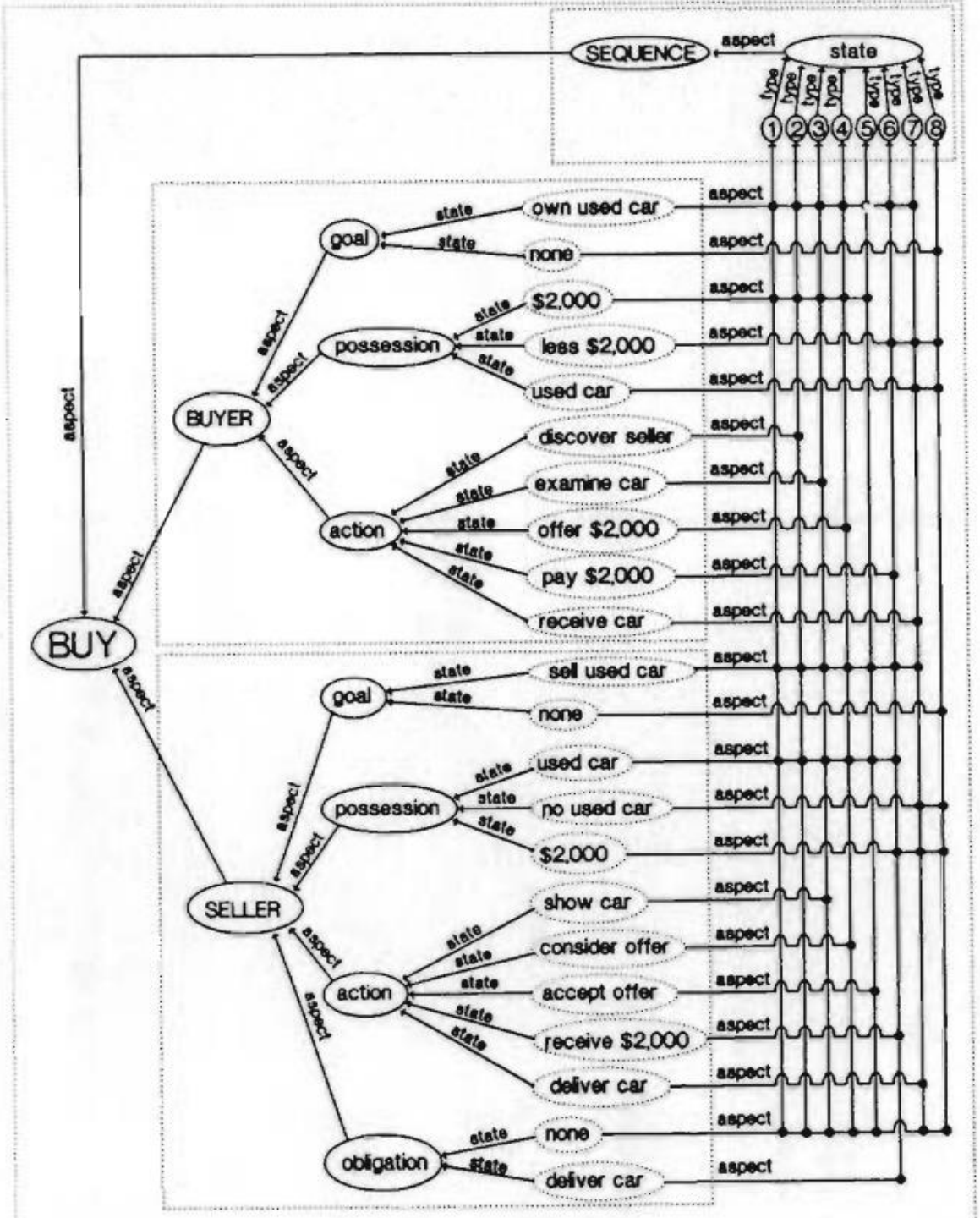
	category				
rank	BIRD	FRUIT	VEHICLE	FURNITURE	WEAPON
top eight					
1	robin	orange	automobile	chair	gun
2	sparrow	apple	station wagon	sofa	pistol
3	bluejay	banana	truck	couch	revolver
4	bluebird	peach	car	table	machine gun
5	canary	pear	bus	easy chair	rifle
6	blackbird	apricot	taxi	dresser	switchblade
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

Horrocks

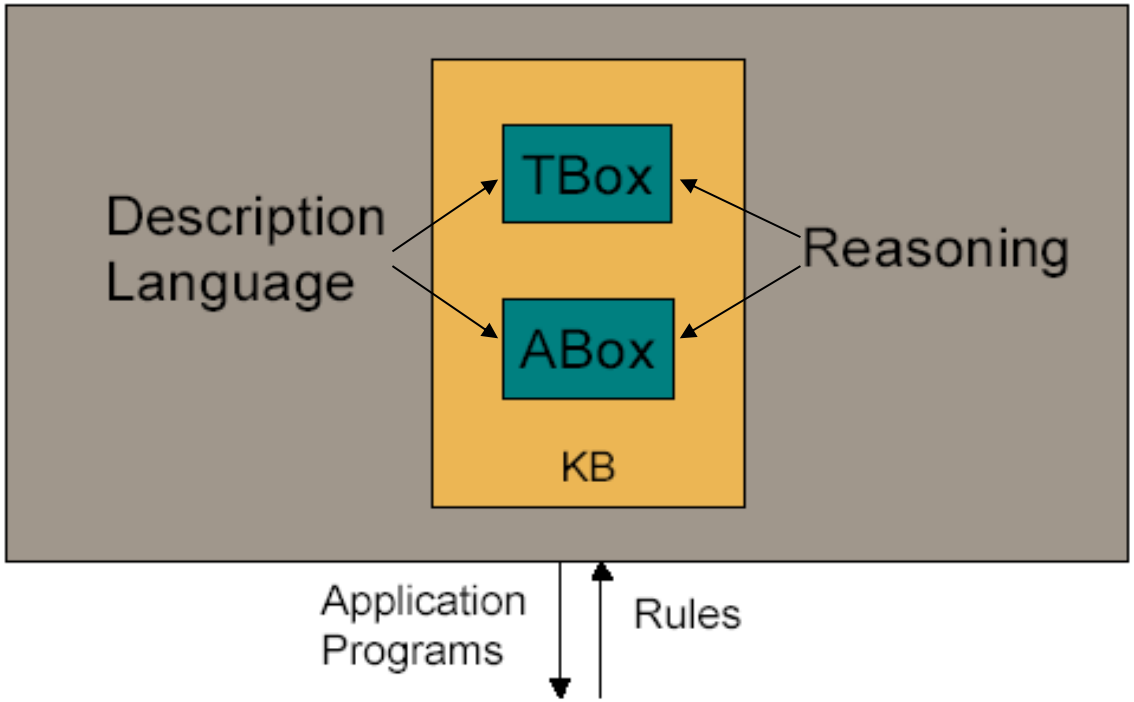
TBox and ABox

- 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).

Horrocks

Architecture of a DL System



Horrocks

Formulas

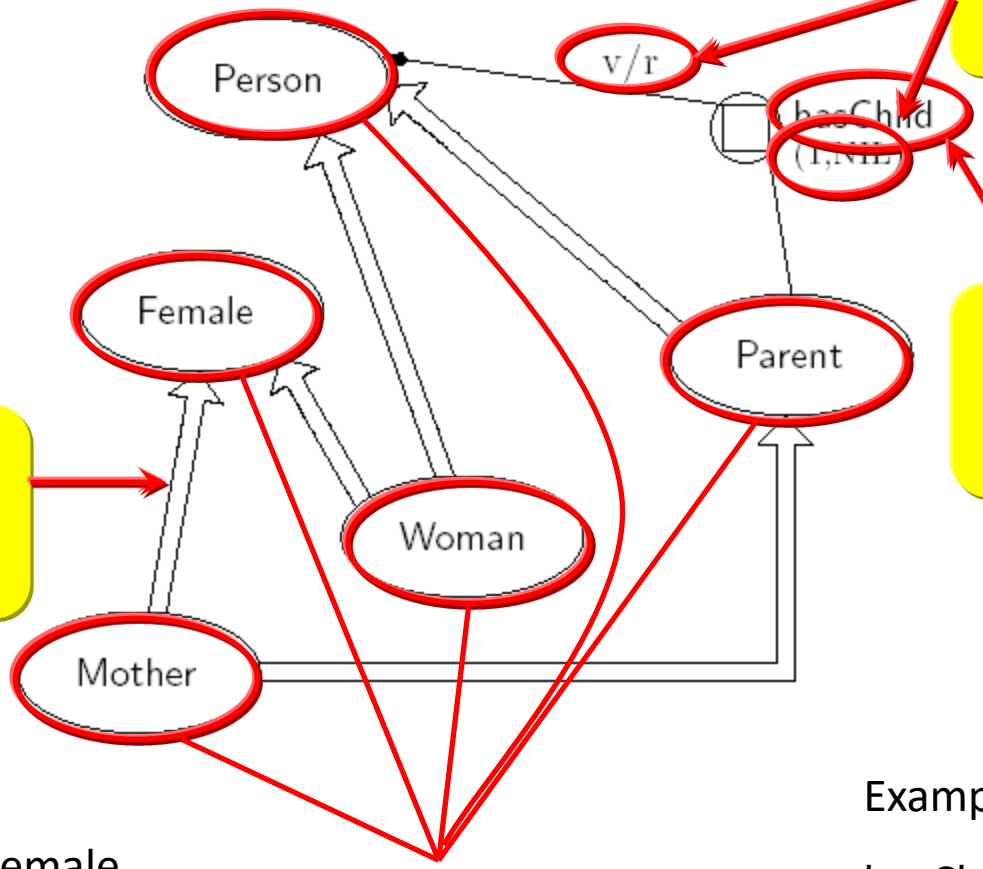
- Building blocks that allow complex descriptions of concepts and roles.
  - Example (we'll look at the syntax in more detail soon.)
    - A Woman is a Female Person
      - Woman = Person **u** Female
    - A Mother is a Woman and she has a child
      - Mother = Woman u hasChild.T

- The TBox can be used to assign names to complex descriptions.

  We will use the terms description and concept interchangeably.

Horrocks

An Example about Family Relationships



value restriction(v/r): (1, NIL)

a *role* defines a property of *Parent: hasChild.Person*

"IS-A" relationship defines a hierarchy over concepts

These are concepts

Examples in TBox:

Woman ´ Person u Female

Mother ´ Woman u hasChild.Person

Examples in ABox:

hasChild(MARY, PETER)

Father(PETER)

Name Symbols vs. Base Symbols

- Atomic concepts occurring in a TBox **T** can be divided into two sets, <u>name symbols N_T</u> (or defined concepts) and <u>base symbols B_T</u> (or primitive concepts, occur only on the right-hand side)

- A <u>base interpretation</u> for **T** only interprets the base symbols.

Base symbols

Name Symbol

$$
\begin{aligned}
\text{Woman} &\equiv \text{Person} \sqcap \text{Female} \\
\text{Man} &\equiv \text{Person} \sqcap \neg\text{Woman} \\
\text{Mother} &\equiv \text{Woman} \sqcap \exists\text{hasChild.Person} \\
\text{Father} &\equiv \text{Man} \sqcap \exists\text{hasChild.Person} \\
\text{Parent} &\equiv \text{Father} \sqcup \text{Mother} \\
\text{Grandmother} &\equiv \text{Mother} \sqcap \exists\text{hasChild.Parent} \\
\text{MotherWithManyChildren} &\equiv \text{Mother} \sqcap \geqslant 3\,\text{hasChild} \\
\text{MotherWithoutDaughter} &\equiv \text{Mother} \sqcap \forall\text{hasChild.}\neg\text{Woman} \\
\text{Wife} &\equiv \text{Woman} \sqcap \exists\text{hasHusband.Man}
\end{aligned}
$$

Horrocks

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)

Horrocks

OWL Class Constructor

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

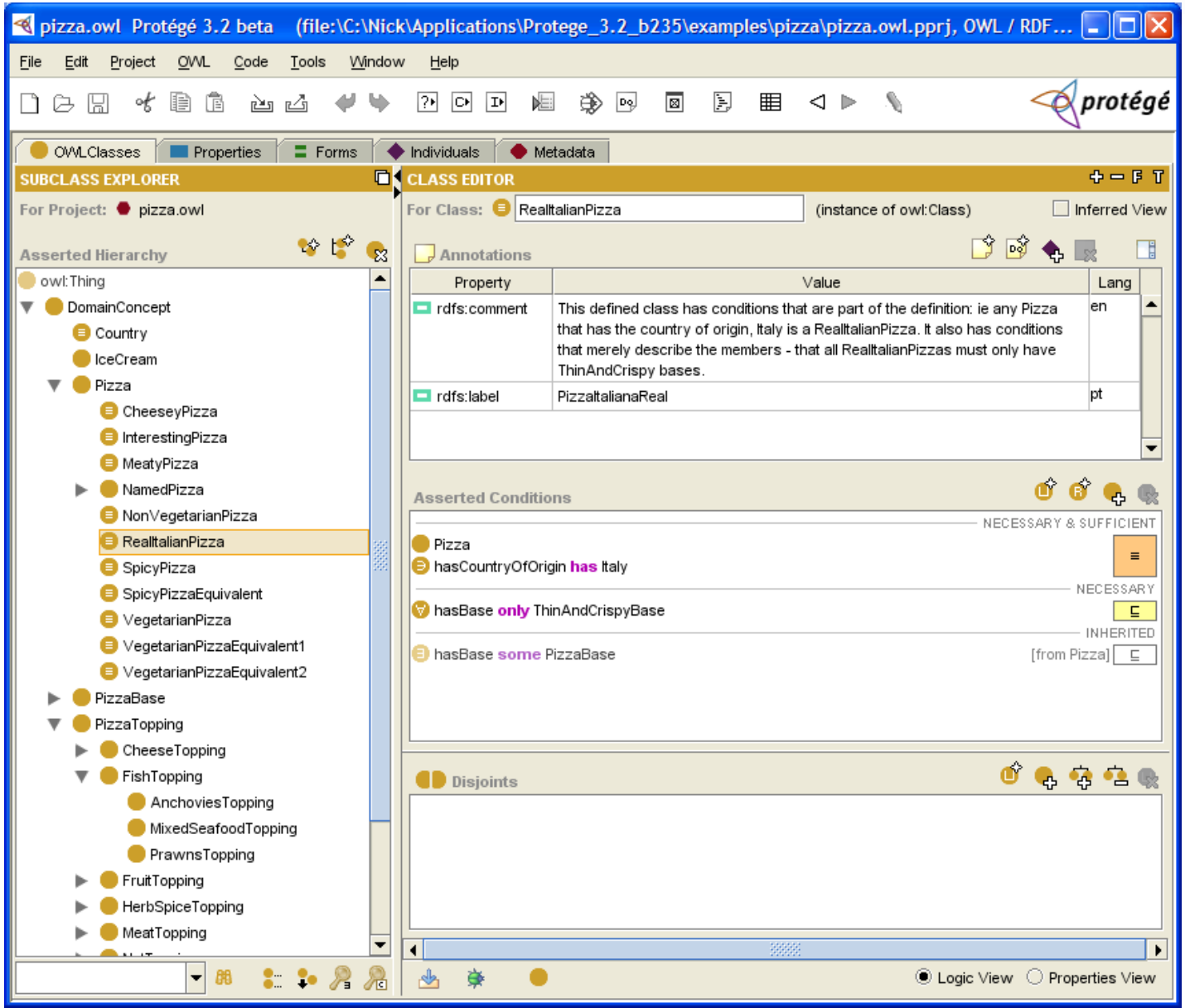
Horrocks

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	$\top \sqsubseteq \leqslant 1 P$	$\top \sqsubseteq \leqslant$1hasMother
inverseFunctionalProperty	$\top \sqsubseteq \leqslant 1 P^-$	$\top \sqsubseteq \leqslant$1hasSSN$^-$

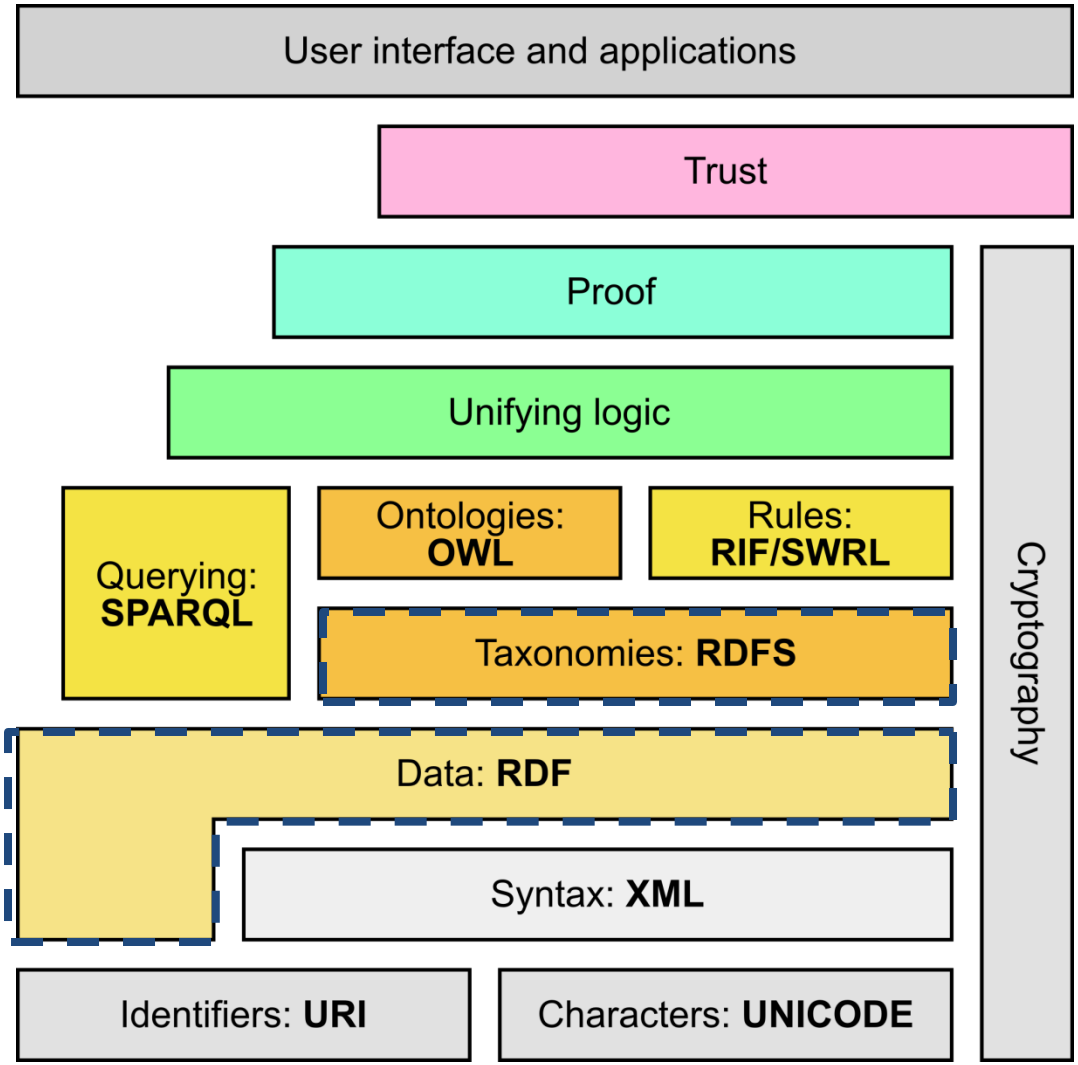
Horrocks

Ontology Editors



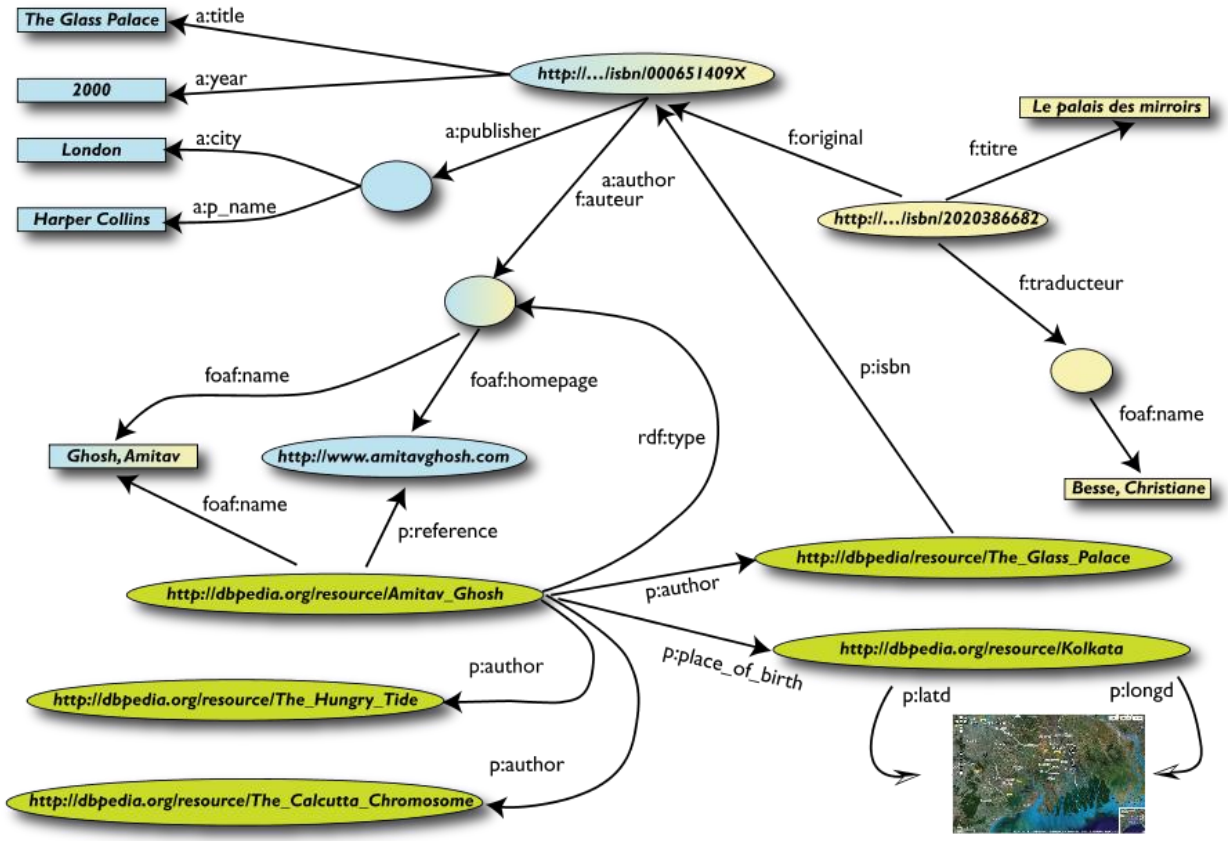
Semantic Web

Semantic Web Stack



RDF: a Direct Connected Graph based Model

- Different interconnected triples lead to a more complex graphic model.
- Basically a <u>RDF document</u> 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

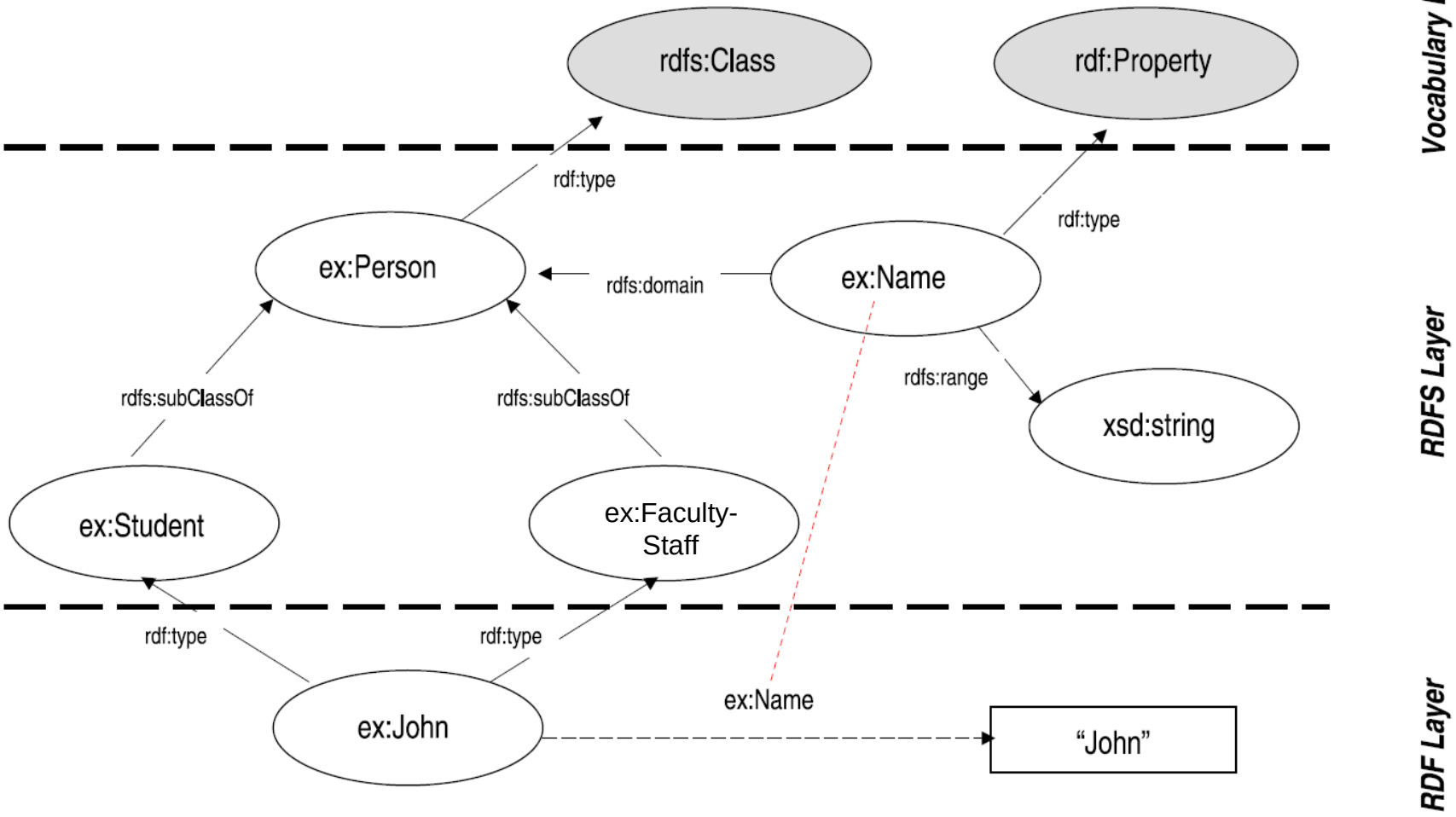
RDFS Classes

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

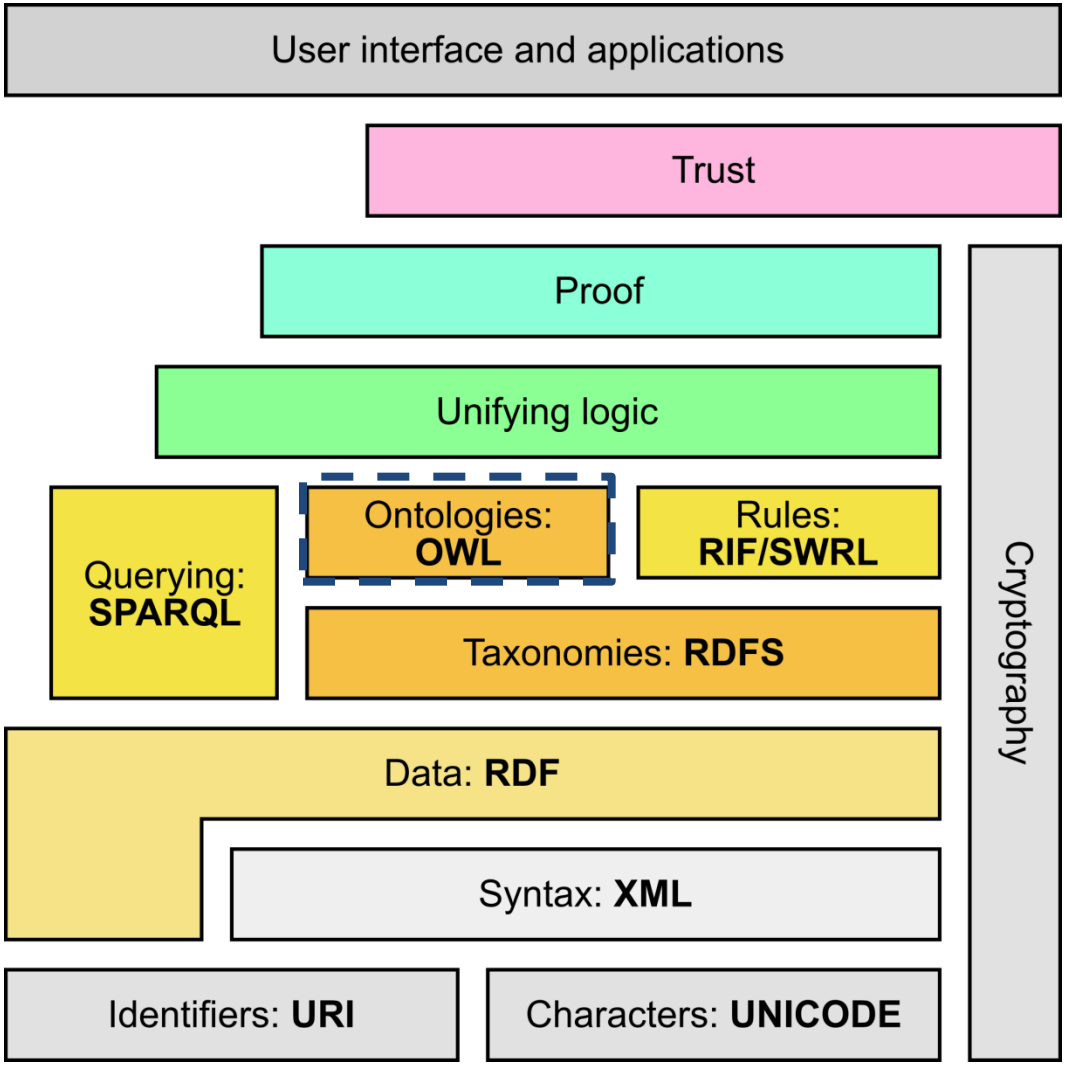
RDFS Properties

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

RDFS Example

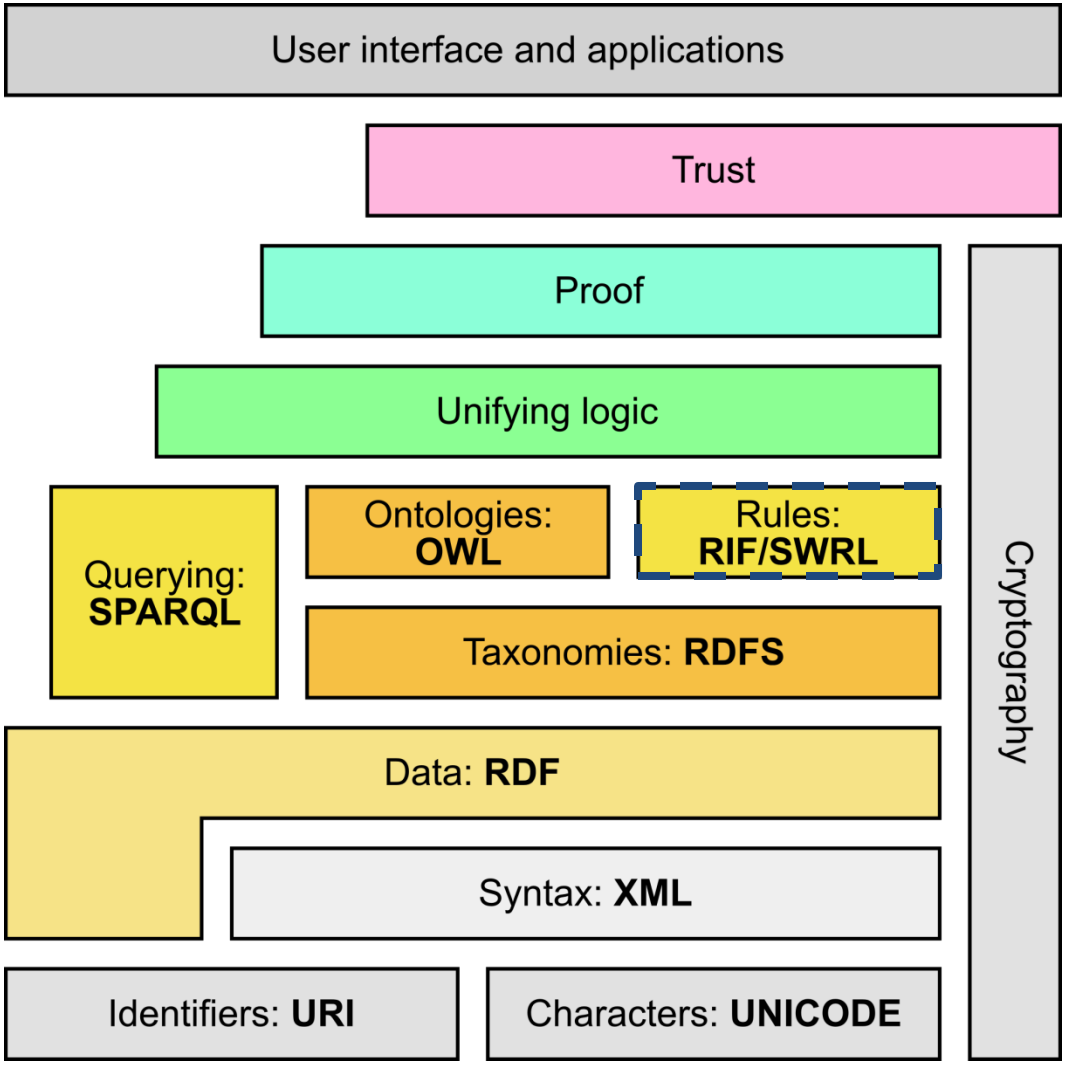


Semantic Web Stack



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

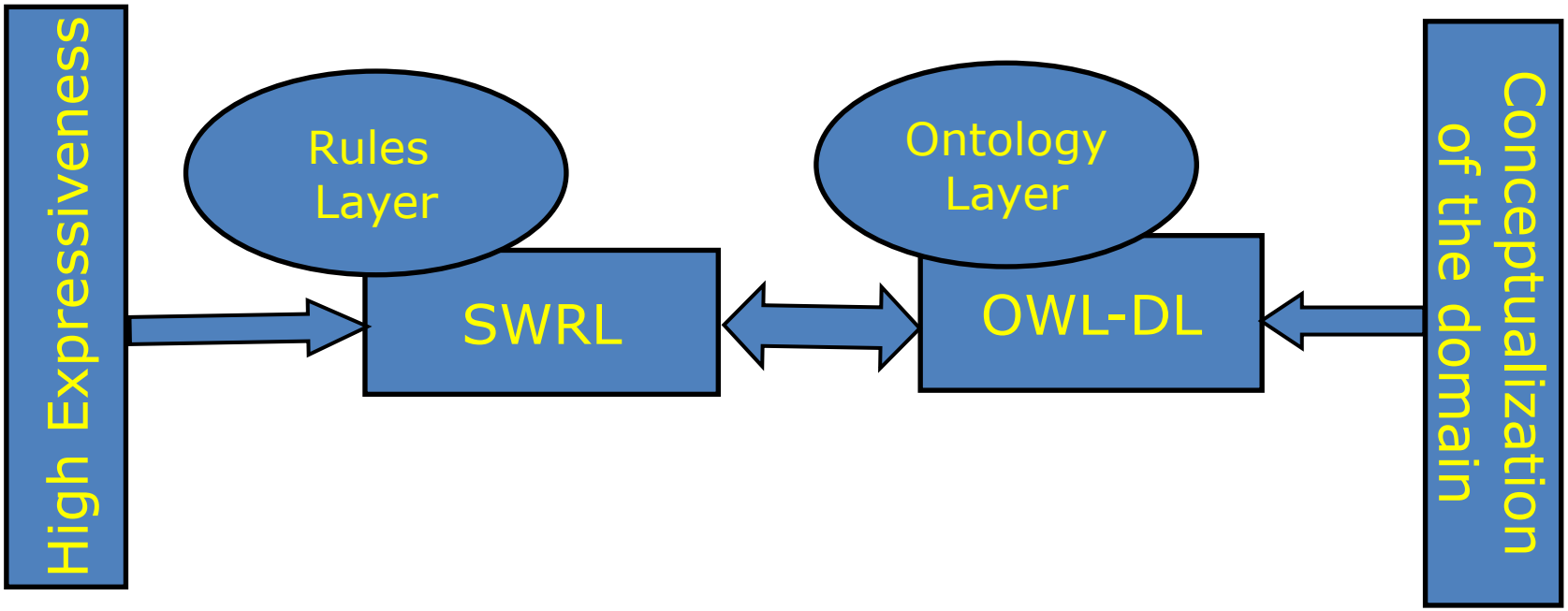
Semantic Web Stack



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,...)***

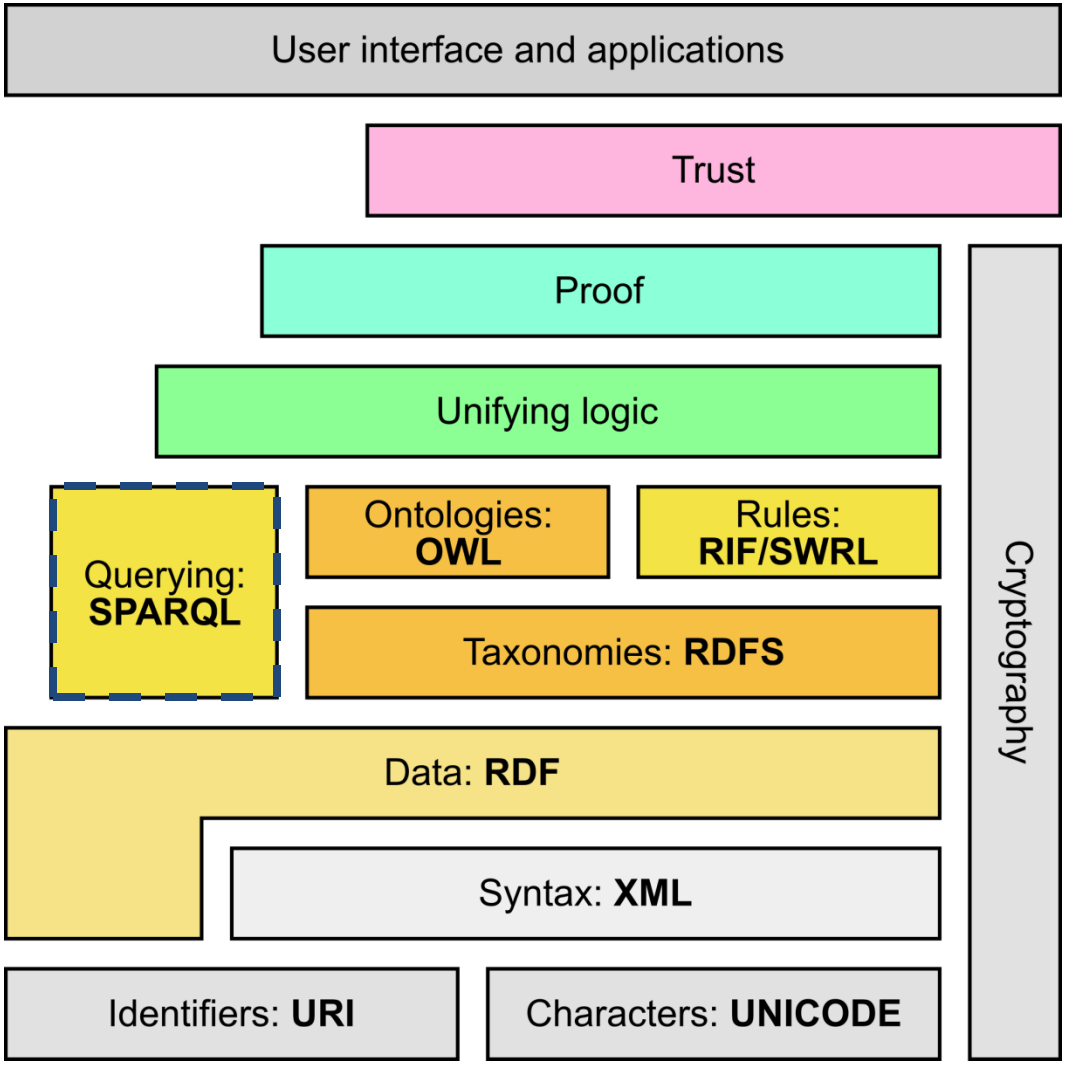
- **P** is a predicate symbol (classes, properties...)
- Arguments of the expression: ***arg1, arg2,…*** (individuals, data values or variables)

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

de.dbpedia.org/sparql

Virtuoso SPARQL Query Editor

Default Data Set Name (Graph IRI)

Query Text

```
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/