Semantic Data

Chapter 5 : Ontologies and ontology engineering
Part 1 : Ontolologies

Jean-Louis Binot

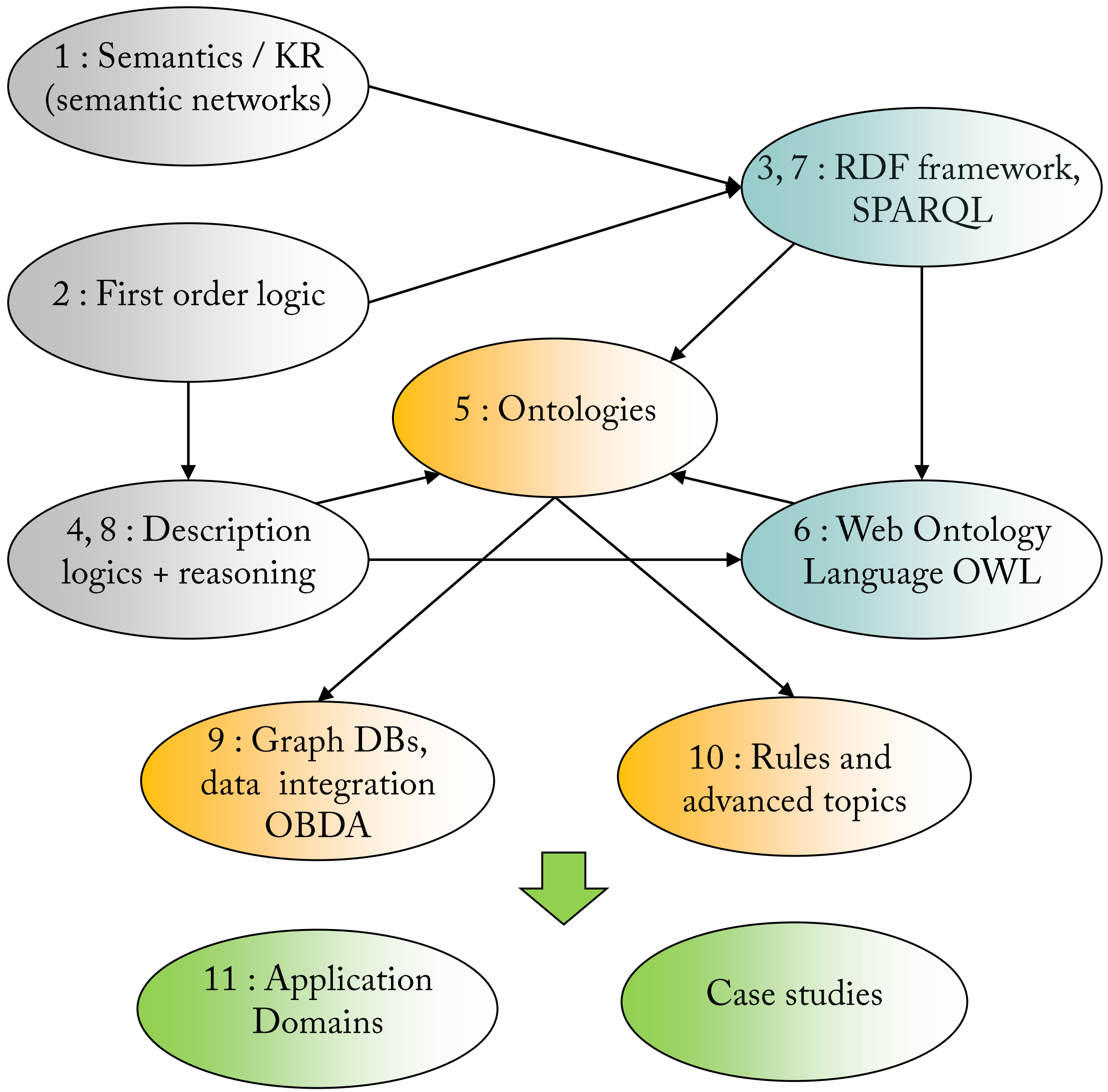
Course content outline

Credits : 5 (theory 25 h, practice 10 h, project 45 h)

Theory (25 h):

1. Semantics and knowledge representation.
2. Introduction to first order logic.
3. The semantic web resource description framework.
4. Description logics.
5. Ontologies and ontology engineering.
6. The Web Ontology Language : OWL.
7. Querying the semantic web : SPARQL.
8. Reasoning with description logics.
9. Data integration and ontology-based data access.
10. Rules and advanced topics.
11. Application domains for semantic data.

Case studies : real cases for genuine business customers; integrated in the relevant theory sessions.



Sources

- There are no additional required references for this chapter.

- Sources and useful additional readings :

  - *Towards Principles for the Design of Ontologies Used for Knowledge Sharing, Gruber, 1993*, and *Ontologies and Semantics for Seamless Connectivity, Ushold and Gruninger, 2004.*
  - The introduction *What is an ontology?* of the *Handbook on Ontologies 2nd edition, 2009,* except for the mathematical aspects of the notion of conceptualization *(Guarino et al. 2009).*
  - The *Semantic Web Primer, Antoniou and Van Harmelen, 2004.*

- University courses having partially inspired ideas and examples for this chapter :

  - *Ontologies and Ontological Analysis: An Introduction* (*Guarino 2008),* and *Ontologies and the Semantic Web: Building Blocks and Challenges (van Elst and Sintek 2008),* Tutorials of the 5th international conference on formal ontology in information systems, Saarbrucken, 2008.
  - *Introduction aux Ontologies*, B. Espinasse, University of Aix-Marseilles, 2010.
  - *Semantic Web Technologies, H. Paulheim,* Universität Manheim.

Agenda

1	Ontological commitment
2	Types of ontologies
3	Upper ontology knowledge
4	Examples of modern ontologies

Computer Sciences ontologies

- In the introduction we used this definition from Gruber :

  In the context of computer and information sciences, an ontology defines a set of representational primitives with which to model a domain of knowledge or discourse. The representational primitives are typically classes (or sets), attributes (or properties), and relationships (or relations) among class members (Gruber, Encyclopedia of Database Systems, 2009).

- There are many other definitions of ontologies. Two widely referred ones :

  *An **ontology** is an explicit specification of a conceptualization* (Gruber, 1993).

  An ontology is a formal specification of a shared conceptualization (Borst, 1997).

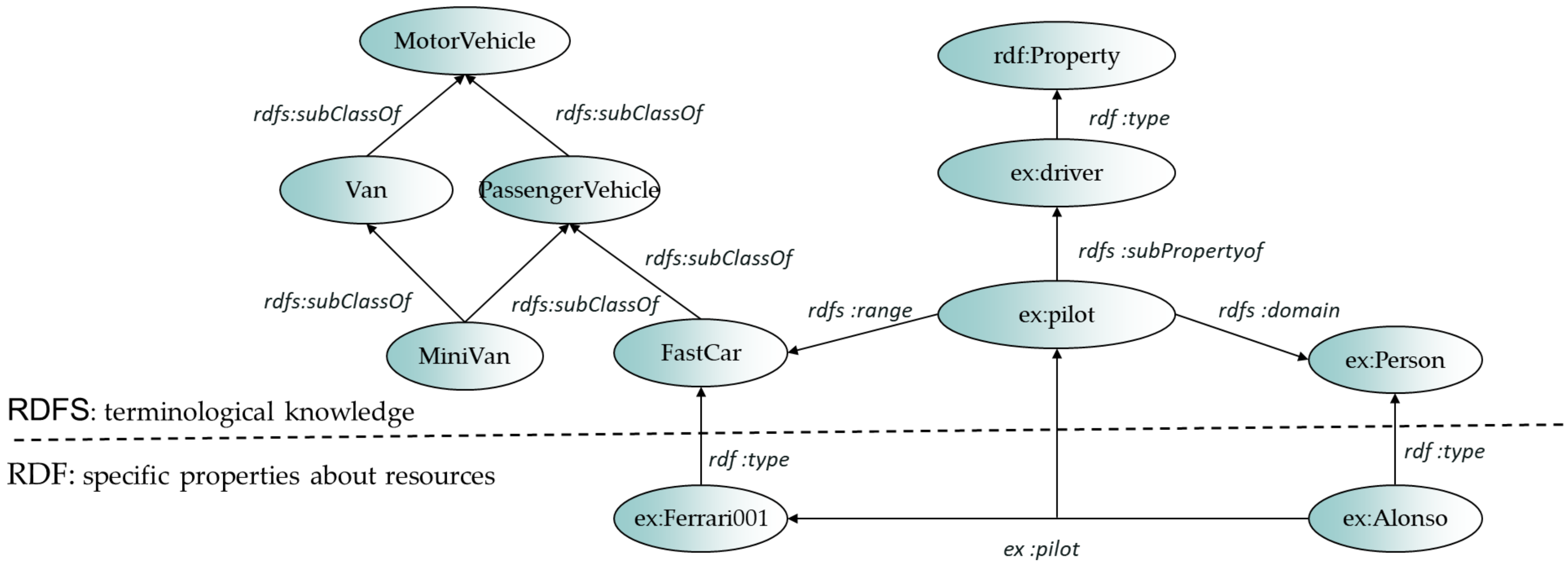
- Conceptualization ?
- Shared ?
- Formal ?

A conceptualisation ?

- Definition most often referred to *(Genesereth and Nilsson 1987) :*

A body of formally represented knowledge is based on a conceptualization : the objects, concepts, and other entities that are assumed to exist in some area of interest and the relationships that hold among them. A conceptualization is an abstract, simplified view of the world that we wish to represent for some purpose. Every knowledge base, knowledge-based system, or knowledge-level agent is committed to some conceptualization, explicitly or implicitly.

- The example below from chapter 3 is a simple conceptualization (in RDFS).



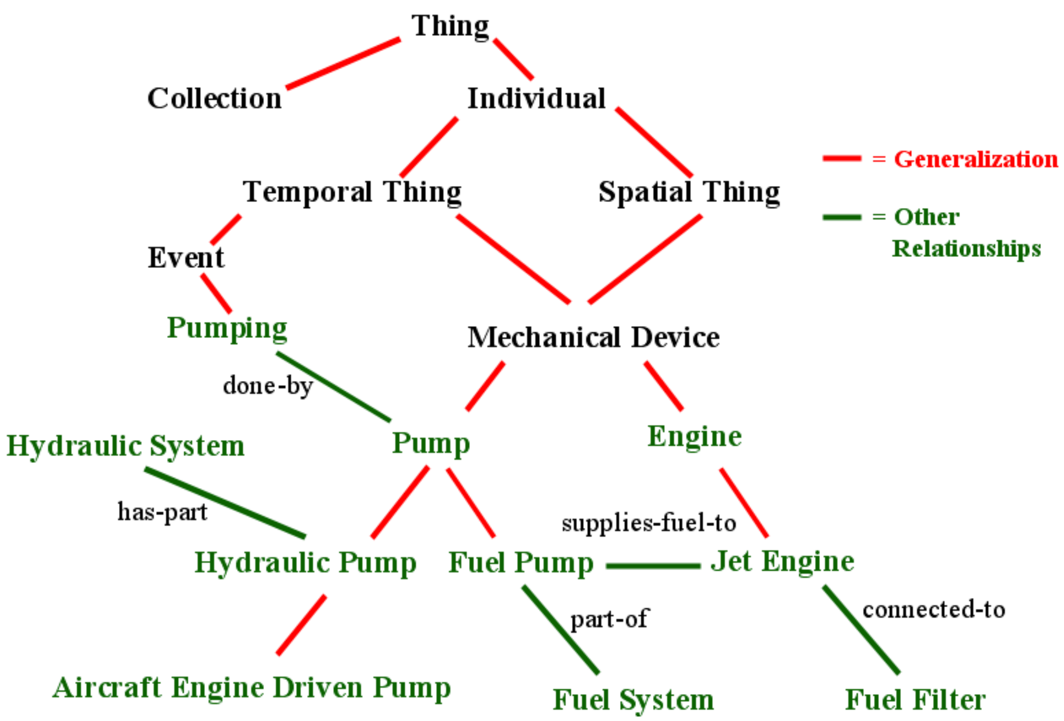
Industrial example

Fragment of ontology developed for an aircraft company (shown before in the course).

Formalization in OWL (Web ontology language).

Main relationships illustrated :

- The generalization / specialization hierarchy.
- part-of and its reverse has-part.
- done-by (instrument).



(from Ushold and Gruniger 2004)

Formal ?

- *Formal refers to the fact that the ontology should be machine-readable* (Studer et al. 1998).

  Is that definition OK ?

- No, we require more. We require a formal specification based on :
  - A formal syntax => non ambiguous, shared and used in the same way by all;
  - Formal semantics => understood in the same way, supporting formal reasoning.

Why sharing ?

- Multiple levels of communication :
  - Between humans, between humans and computer, between computer agents.
- Integration of multiple domains.
  - In a health environment for example : medical (diseases, treatments, drugs), financial (payments), organizational (hospitals), temporal (schedules), spatial (addresses)…
- High risks of miscommunication during information access and data integration.
  - Concepts with different names, potentially conflicting statements, rules or data…

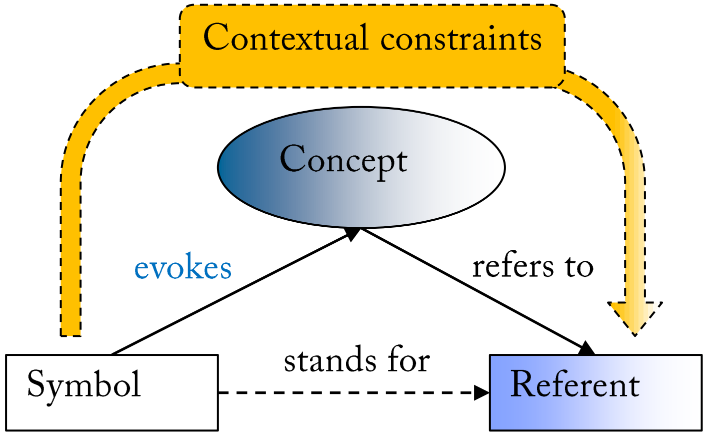
Ontologies are used to share knowledge and facilitate communication.

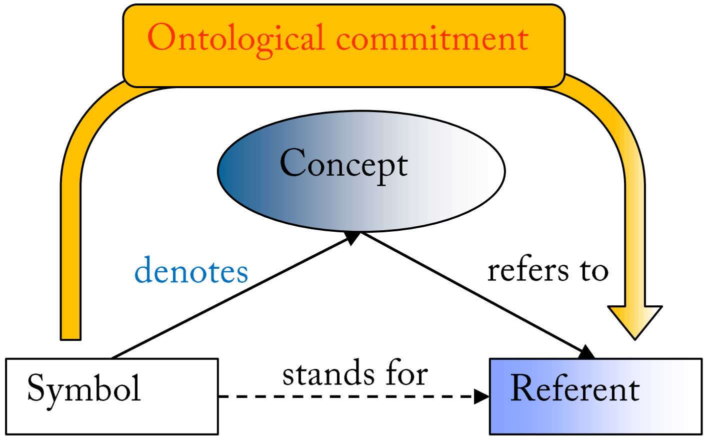
- By formalizing and sharing conceptualizations, they improve greatly the capability to refer to the same things by using the same symbols.

Why sharing ? ./.

Let us go back to the meaning triangle (cf. chapter 1) :

- Correspondences between symbols, concepts and referents are highly ambiguous.
  - They differ between sender and receiver(s).
  - The relation between symbol and concept is imprecise.
  - Context may constraint and disambiguate meaning, but usually not enough.
- Sharing a common ontology strongly reduces ambiguity :
  - The set of concepts and relations is commonly defined.
  - The underlying logical theory define the meaning of concepts and limits interpretations.
  - The relation between symbol and concept becomes much stronger.





(after Guarino et al. 2009)

Ontological commitment

Ontological commitment is an agreement to use the definitions of a specific (shared) ontology.

> *We use common ontologies to describe* ***ontological commitments*** *for a set of agents so that they can communicate about a domain of discourse without necessarily operating on a globally shared theory. We say that an agent* ***commits*** *to an ontology if its observable actions are consistent with the definitions in the ontology…*
>
> *Pragmatically, a common ontology defines the vocabulary with which queries and assertions are exchanged among agents. Ontological commitments are agreements to use the shared vocabulary in a coherent and consistent manner.* (Gruber 1993).

Agenda

1	Ontological commitment
2	Types of ontologies
3	Upper ontology knowledge
4	Examples of modern ontologies

Upper and domain ontologies.

To capture everything in a single ontology is impossibl

- ❑ Ontologies are typically divided into layers :

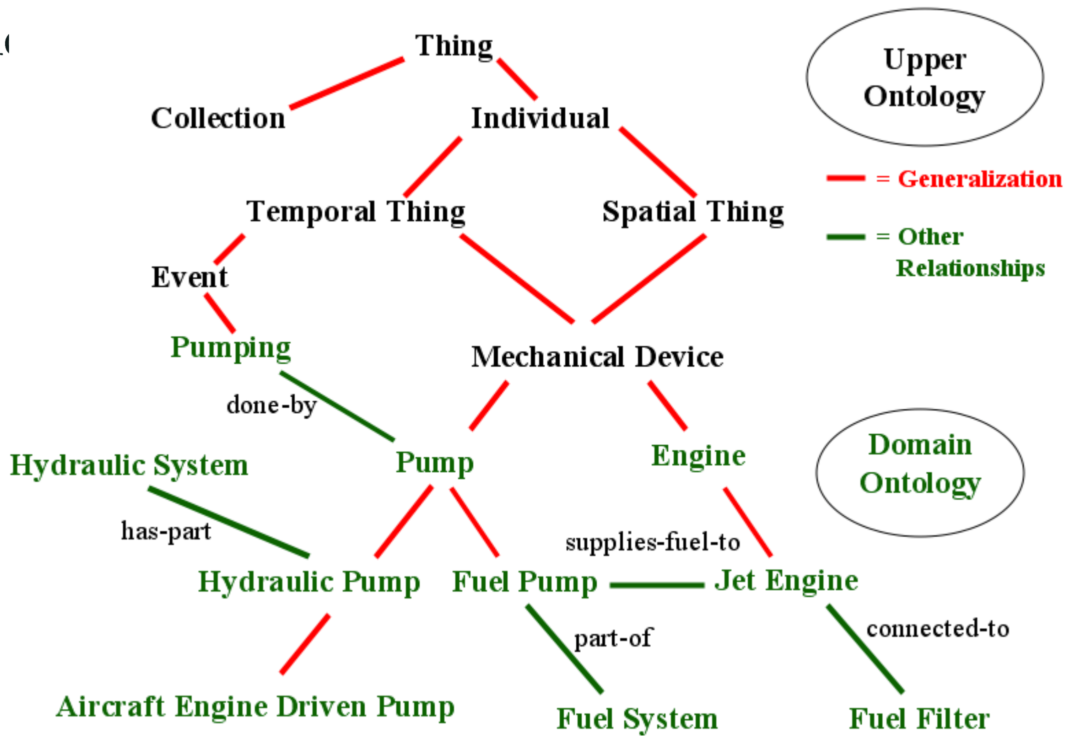
➢ Upper ontology :

- Captures domain-independent general concepts, about space, time, causality, objects …

➢ Domain ontology :

- Adds (domain-dependent) models of domain-related concepts and relations.

- ❑ An upper ontology can be reused by many domain ontologies (if well done).

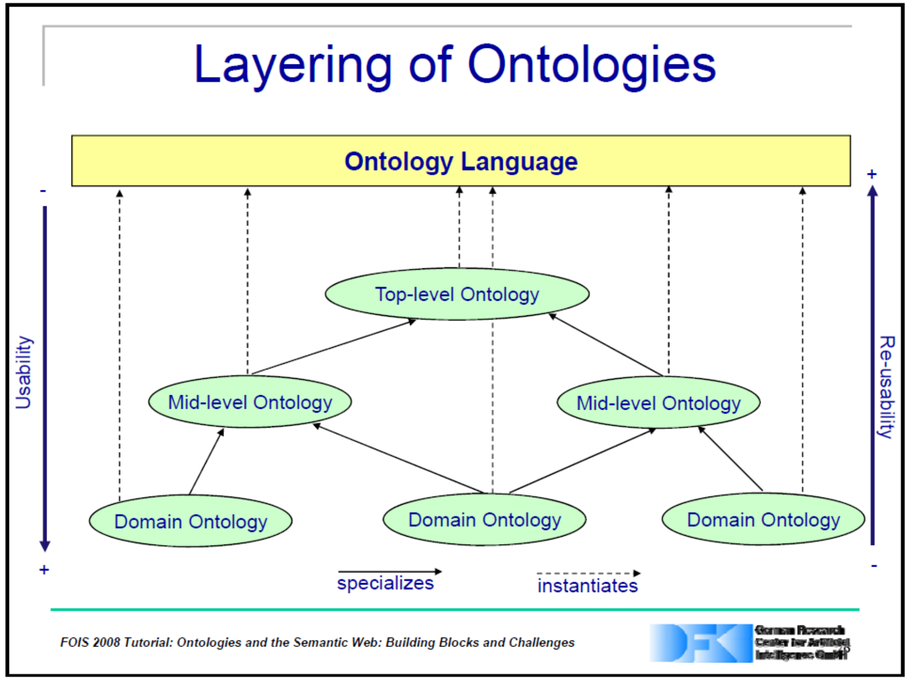


(Fragment of ontology developed for an aircraft company from Ushold and Gruniger 2004)

Three levels of ontologies

To increase reuse, three layers have been proposed :

- Top-level ontology: general concepts of the world, about space, time, causality, objects;
- Middle-level ontology: the general concepts of a broad domain;
- Domain ontology: the specialized concepts of a specific domain.



(from van Elst and Sintek 2008)

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What does an upper ontology contain ?

- An upper ontology contains reusable knowledge about the world.
  - It contains a reusable classification of categories, but this is not enough.
  - An axiomatic characterization of background knowledge is also needed.
  - Such an axiomatization is provided in a formal language (FOL or related).

- Example: consider Newton's law :

$$F = ma$$

Its understanding requires knowledge on :

- Mathematical expressions, equations, variables …
- Physical meaning of variables (m means mass and not electrical resistance).
- Background mechanical knowledge (properties of mass, force …) etc.

What does an upper ontology contain ? ./.

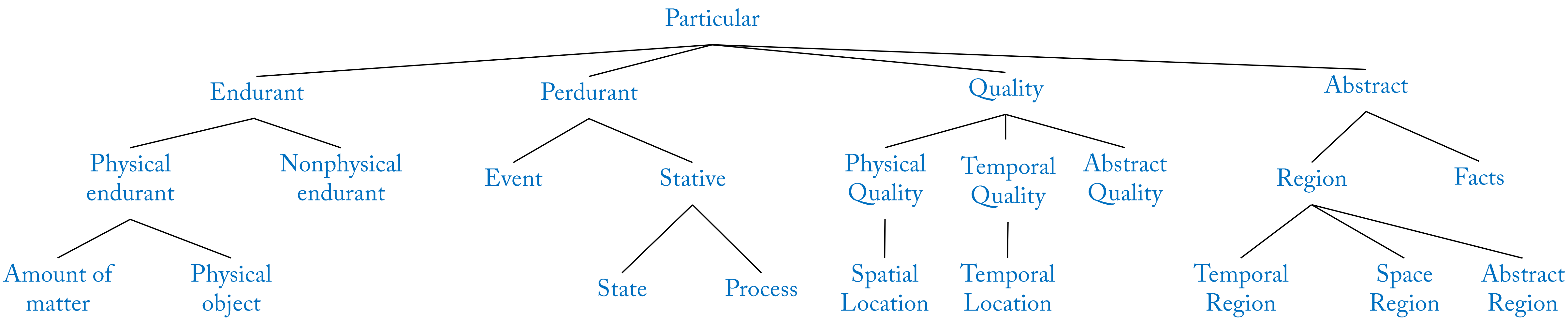
Typical knowledge domains include (varies per ontology) :

- Categories and their classification.
- Objects.
- Processes and events.
- Qualities, measurements.
- Space, time.
- Mereotopology (mereology, topology).
- …

(the discussion on these topics is inspired from the DOLCE documentation (Masolo et al. 2003), the course Semantic Web Technologies from H. Paulheim, Universität Manheimn, and (Russel and Norwig 2010)).

A starting guide : the top level of the DOLCE ontology

- Dolce (*Descriptive Ontology for Linguistic and Cognitive Engineering*)
  - Developed at the Laboratory for Applied Ontology (Trente, Italy); still active.
  - Upper-level ontology with axioms described in first order logic. Main part downloadable in OWL.
- All upper ontologies differ. DOLCE is a good starting point for the main ideas.

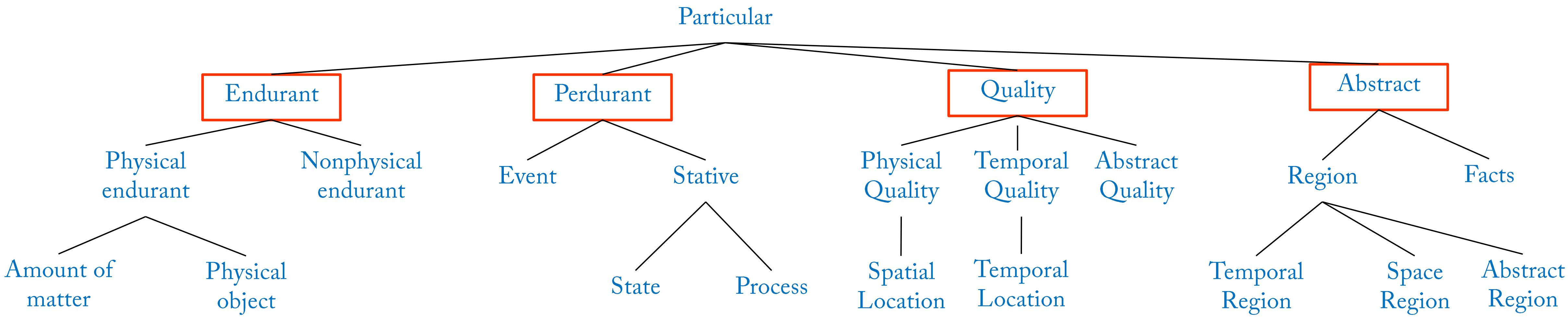


An excerpt from DOLCE ontology (from DOLCE site)

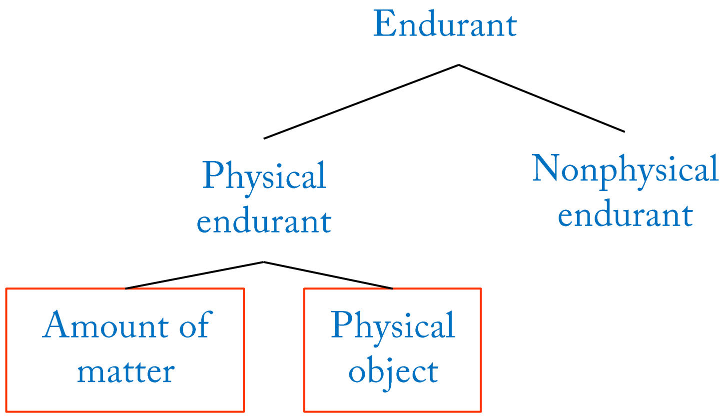
A starting guide : the top level of the DOLCE ontology

4 main categories, pairwise disjoint :

- Endurants (3D) exist in time : physical (e.g. books) and nonphysical (e.g. organizations).
- Perdurants (4D) happen in time : mainly events and processes.
- Qualities are attached to endurants and perdurants.
- Abstracts include numbers, measure units, space and time concepts.



Objects and Matter



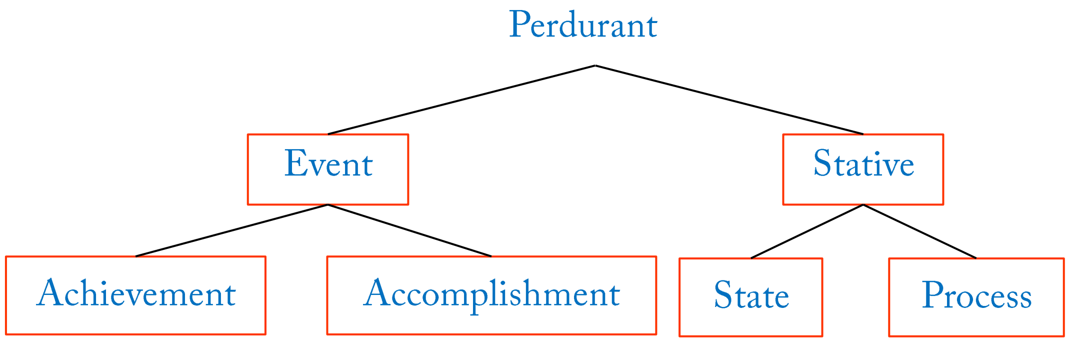
Physical endurants can be abstracted into :

- Physical objects (things, count nouns).
  - They have individuation : they can be identified as distinct objects.
  - They are not mereologically invariant : an apple being cut is no longer an apple.
  - They have extrinsic properties : which are not retained under subdivision (weight, size, shape …).
- Amount of matter (stuff, mass nouns).
  - They are mereologically invariant and resist individuation : butter being cut is still butter.
  - They have only intrinsic properties : retained under subdivision (melting point, density…).

  b ∈ Butter ∧ PartOf (p, b) -> p ∈ Butter

  b ∈ Butter -> MeltingPoint(b, Centigrade(30))
- How would you represent a pound of butter ?

States, events and processes



- Statives.
  - Statives add their duration.

    The combination of two "sleeping" is a "sleeping" of a longer time.
  - States consist only of states of the same type (sitting or sleeping).
  - Processes may combine processes of different types (studying : reading, working, presenting results…).
- Events.
  - Events do not add their duration.

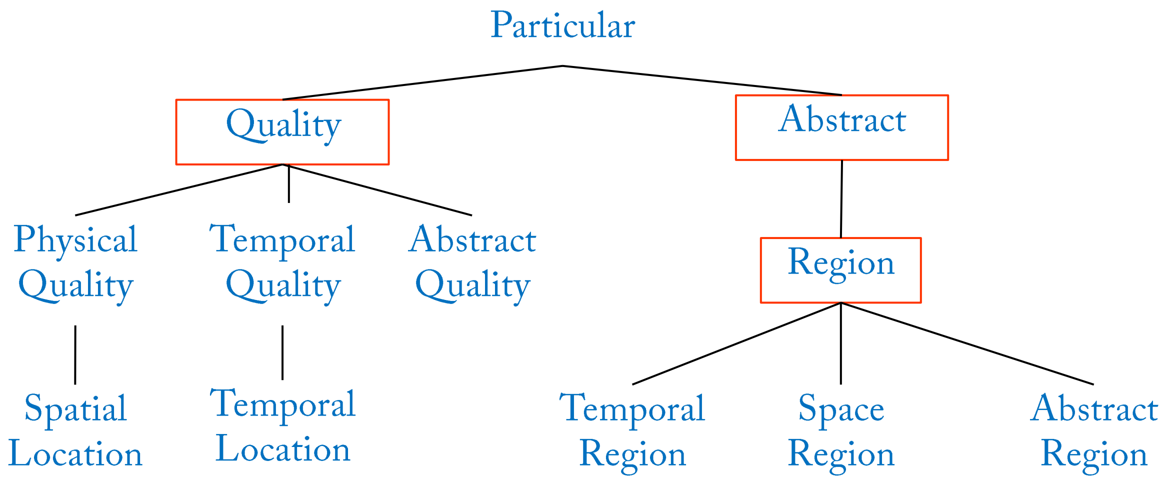
    The combination of two "flying to the moon" is not a "flying to the moon" for a longer time.
  - They may be further classified into Achievements (non dividable) and Accomplishments (dividable).

    Achievement: reaching Paris.

    Accomplishment: going to China.

Qualities and measures

- Qualities have values taken in quality spaces.
  - A quality is a property of an entity.
  - A quality space characterizes the set of values of the quality.
  - Each quality type has its own quality space, which is an abstract region.
  - Space and time locations are qualities, taking their values in the Temporal and Space regions.



Qualities and measures ./.

- Most scientific and commonsense theories use measures.

- In Dolce measures are quality values.
  - Each related quality space may have a specific structure.

  E.g. length is usually associated to a metric linear space.

  - Quantitative measures usually have a (system of) unit(s) and may require conversions.

  Centimeters(2,54*d) = Inches(d) *(may be captured by SWRL rules, seen later)*

  - Qualitative measures may be described by enumerated sets.

  Color = {red, yellow…}

- Complex axiomatizations may be applied (time intervals, fuzzy sets …).

Property axioms

- Properties of entities may have specific relational properties. These relational properties can be axiomatized in FOL (role axioms in description logics).

- A property is transitive iff $\forall x \ \forall y \ \forall z \ (P(x, y) \land P(y, z) \rightarrow P(x, z))$.
  - The range of a transitive property must be subsumed by its domain (why ?).

  In DL : *Trans(partOf)*

- A property is symmetric iff : $\forall x \ \forall y \ (P(x, y) \rightarrow P(y, x))$.
  - The domain and range of a symmetric property must be the same (why ?).

  In *DL* : adjacentRegion ≡ adjacentRegion^{-}

- A property is functional iff $\forall x \ \forall y \ \forall z \ (P(x, y) \land P(x, z) \rightarrow (y = z))$.

  In *DL* : $\top \subseteq (\leq 1 \ \text{hasMother})$

- Two properties P and Q are inverse of each other iff $\forall x \ \forall y \ (P(x, y) \leftrightarrow Q(y, x))$.

  In DL : hasChild ≡ childOf^{-}

Additional relations between classes

- In addition to the specialization hierarchy, additional relations are needed :

  If we only state that Male and Female are subclasses of Animal, a Male individual could also be a Female.

- Disjoint :
  - FOL : Disjoint(s) $\equiv \forall c1, c2\ (c1 \in s \land c2 \in s \land c1 \neq c2 \rightarrow \text{Intersection}(c1, c2)=\{\ \})$
  - DL : $C1 \sqcap C2 \sqsubseteq \bot$
  - Example : Disjoint({Animals,Vegetables})

- Disjoint union :
  - FOL : ExhaustiveDecomposition(s, c) $\equiv \forall i\ (i \in c \leftrightarrow \exists c1\ (c1 \in s \land i \in c1))$
    DisjointUnion(s, c) $\equiv$ Disjoint(s) $\land$ ExhaustiveDecomposition(s, c)
  - DL : $C \equiv C1 \sqcup C2; C1 \sqcap C2 \sqsubseteq \bot$
  - Example : DisjointUnion({LeftHemisphere, RightHemisphere}, BrainHemisphere)
  - These relations are useful enough to have a specific definition in OWL2.

Mereology

- Mereology (from the Greek μέρος, meros, “part“) :
  - The study of physical composition, of abstract relations between parts and wholes.

- Objects may be grouped into partOf hierarchies :

partOf (Liège, Belgium).
partOf (Belgium, WesternEurope).
partOf (WesternEurope, Europe).
partOf (Europe, Earth).

- The partOf relation is transitive and reflexive :

FOL : partOf (x, y) ∧ partOf (y, z) → partOf (x, z) .

partOf (x, x) .

From the above, we can conclude partOf (Liège , Earth).

Mereology ./.

- partOf hierarchies are not subsumption hierarchies !
  - They do not support inheritance in the same fashion and have their own axiomatization.

An engine is a part of a car but is not a car.

- Some additional useful relations (FOL):
  - Being a proper part : this relation is asymmetric and irreflexive :

proper-partOf(x, y) ≡ partOf(x, y) ^ ¬ partOf(y, x)

  - Being a direct part :

direct-partOf(x, y) ≡ proper-partOf(x, y) ^ ¬ ∃z (proper-partOf(z, y) ^ proper-partOf(x, z))

  - Overlapping :

overlap(x, y) ≡ ∃z (partOf(z, x) ^ partOf(z, y))

(see e.g. Clarke 1981, Keet 2006)

An mereological example in description logics

TBox : $\text{Femur} \sqsubseteq \text{BodyPart} \sqcap \exists\text{partOf.Leg}$

$\text{HeadOfFemur} \sqsubseteq \text{BodyPart} \sqcap \exists\text{partOf.Femur}$

$\text{FractOfFemur} \equiv \text{Fracture} \sqcap \exists\text{isLocatedIn.Femur}$

$\text{FractOfHeadOfFemur} \equiv \text{Fracture} \sqcap \exists\text{isLocatedIn.HeadOfFemur}$

With the axioms :

$\text{isLocatedIn} \circ \text{partOf} \sqsubseteq \text{isLocatedIn}$

Trans(partOf)

Can one infer that :

$\text{HeadOfFemur} \sqsubseteq \exists\text{partOf.Leg}$? Yes

$\text{FractOfHeadOfFemur} \sqsubseteq \text{FractOfFemur}$? Yes

Note : there are different types of mereological compositions. Being a physical part of something is not the same thing as being located in something.

(example from Baader et al. 2017)

Topology

- Topology (from the Greek τόπος, “topos”, *place*)
  - In formal ontology modeling : a first order theory modeling boundaries between parts.
- The connect relation is symmetrical :

  connect (x, y) ↔ connect (y, x).

  - It can be related to the partOf relation through further axioms (mereotopology), e.g. :

  connects (x, y) → ¬ (partOf (x, y) ∨ partOf (y, x)).

- In some domains, multiple types of connections are possible :

  “*a point of contact (mechanical , electrical) , an area crossing a volume flow (hydraulical , pneumatical) or even something abstract as a field (electro-magnetic)» (Borst and Akkermans 1997).*

  - The solution is to reify the relation connection : connects (c, x, y) ↔ connects (c, y, x).

  Example definition in DL : Connection ⊆ >=2 connectedItems; Connexion(c1); connectedItem(c1, p1) ...

Spatial locations

- An object is distinct from its spatial location.

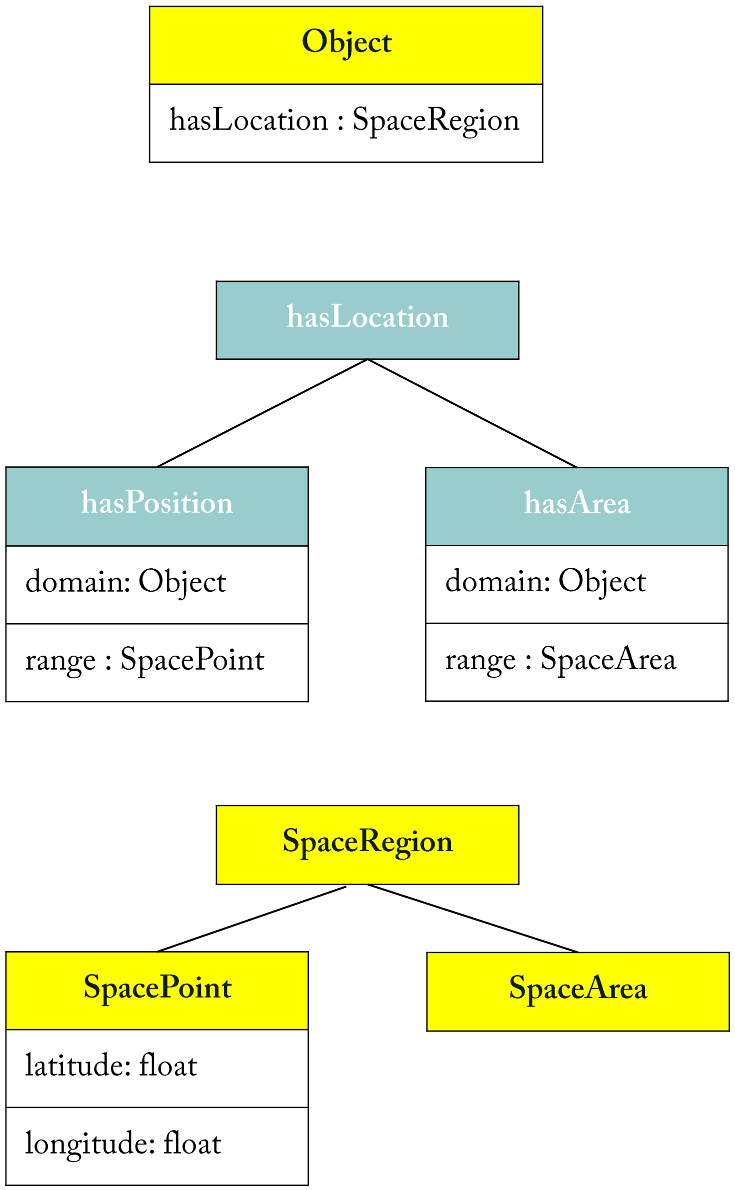
  A city occupies a space area (or volume) but is not a space area.

- An object is linked to a location by a property, e.g. hasLocation.
  - Subproperties hasPosition and hasArea can be specified.

- The value of a space location property belongs to a space region.
  - Different types of spatial locations exist : points, areas, volumes…
  - A position may be represented by a concept SpacePoint with two geographical coordinates properties : latitude and longitude.

    domain : SpacePoint; range : a float interval (degrees with decimals).

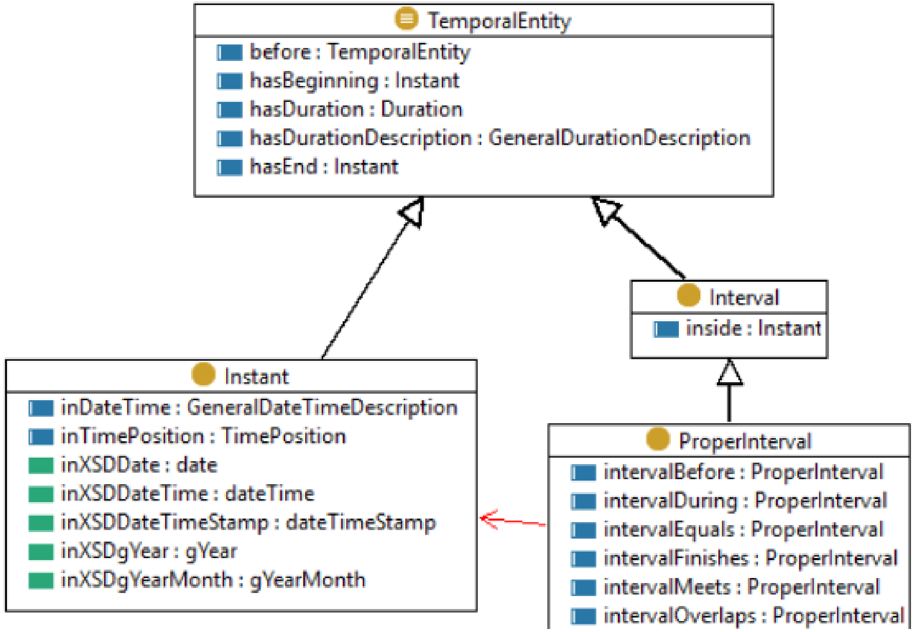
    Range for latitude in RDF(S) / OWL : xsd:float[>= -90.0f , <= 90.0f].
  - An area may be represented by a concept SpaceArea.

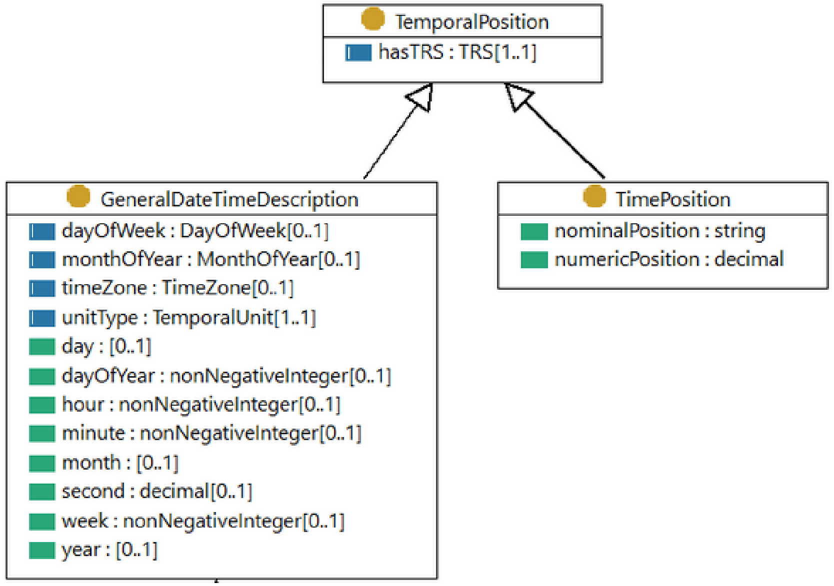


Temporal locations

- We illustrate the basic ideas of a W3C time ontology .
  - Based on an algebra of binary relations on intervals (e.g., *meets*, *overlaps*, *during*) developed by *Allen and Ferguson (1997).*
- A temporal entity is either an instant or an interval.
  - An instant is a special case of an interval with zero duration.
  - A proper interval has distinct beginnings and ends and is disjoint from an instant.
  - Intervals support 13 rigorous relationships between them based on Allen algebra (next slide).
  - A temporal position can be expressed by a simple number or string, or by a general time description.

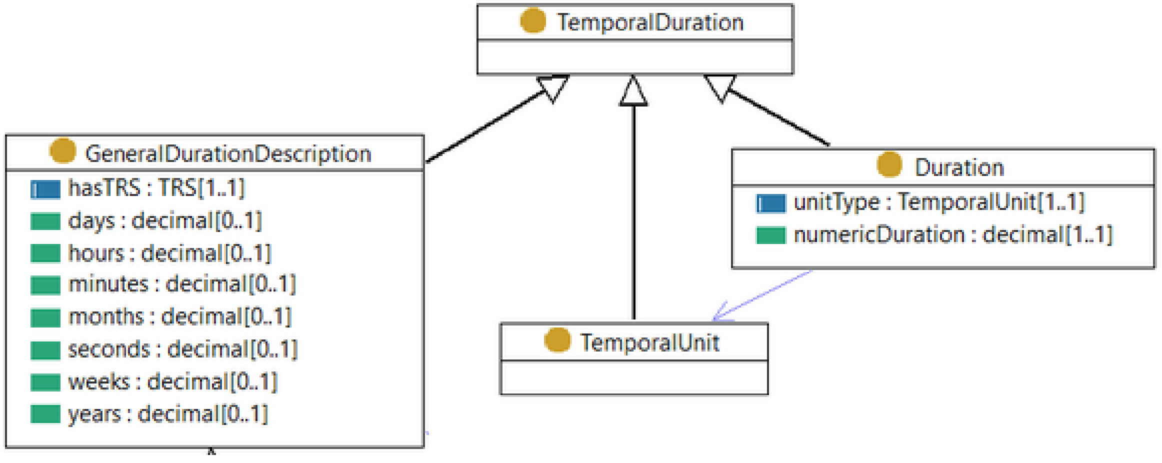
This model can be used in Dolce by relating an object to a temporal entity (subclass of Time Region) by a hasTimeLocation property.





Temporal locations ./.

- Temporal durations can also be expressed
  - Through a simple duration (number of units), or
  - Through a general duration description.



Download in OWL for practice : here.

- Relationships between intervals are based on Allen's algebra.
  - They can be defined in terms of "before" and identity relationships on the beginnings and ends of intervals.

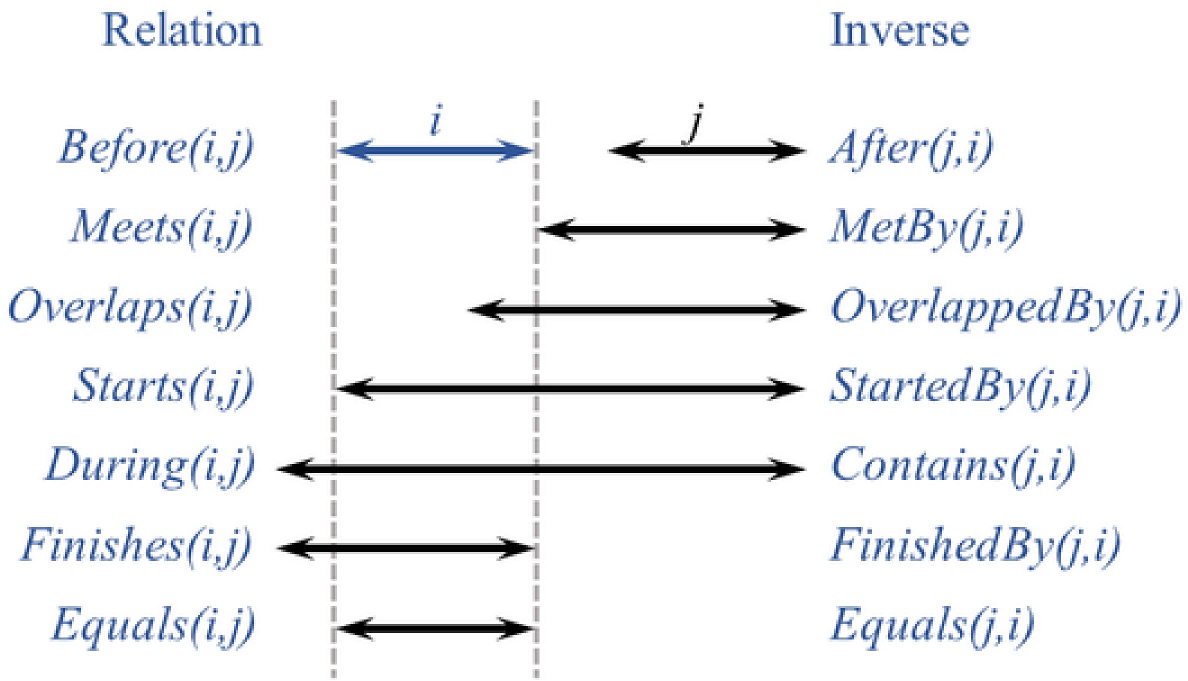


Figure 2 Thirteen elementary possible relations between time periods [af-97].

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Interesting upper / general ontologies

- Dolce (*Descriptive Ontology for Linguistic and Cognitive Engineering*)
- Cyc (*https://www.cyc.com/*)
  - Longest-lived AI effort, started by Doug Lenat in 1984 to build a comprehensive KB of commonsense knowledge.
  - Still developed by CyCorp. More than 500000 terms, thousands of domains.
  - Specific language Cycl : first-order language, with modal operators and higher order quantification.
- Sumo (Suggested Upper Merged Ontology)
  - Developed by Niles and Pease (*2001*), owned by IEEE, free access.
  - Declarative first order language Suo-Kif. Heavily axiomatized : 25000 terms, 80000 axioms.
  - Downloadable in OWL.
  - Has been fully mapped to WORDNET linguistic ontology.

A linguistic ontology of reference : Wordnet

- Linguistic ontology : large lexical database of English.
  - Initially developed by G. Miller at Princeton *(Miller 1995).*
  - More than 15000 words linked by a number of relations but does not rely on explicit formal semantics.
  - Nouns, verbs, adjectives, adverbs grouped into sets of synonyms (synsets), each expressing a concept.
- Synsets are interlinked by means of conceptual-semantic and lexical relations :
  - Hyperonymy (generalization-specialization) and meronymy (part of).
  - Verb troponyms (specific manners of realizing an event : communicate, talk, whisper …).
  - Adjective antonyms (wet-dry …).
- WordNet can be navigated through a browser. Also freely available for download.

(https://wordnet.princeton.edu/)

An example from Wordnet

- S: (n) **bed** (a piece of furniture that provides a place to sleep) *"he sat on the edge of the bed"; "the room had only a bed and chair"*
  - ***direct hyponym*** / *full hyponym*
    - S: (n) berth, bunk, built in bed (a bed on a ship or train; usually in tiers)
    - S: (n) built-in bed (a bed that is built in and fixed to a wall)
    - S: (n) bunk (a rough bed (as at a campsite))
    - S: (n) bunk bed, bunk (beds built one above the other)
    - S: (n) cot, camp bed (a small bed that folds up for storage or transport)
    - S: (n) couch (a narrow bed on which a patient lies during psychiatric or psychoanalytic treatment)
    - S: (n) deathbed (the bed on which a person dies)
    - S: (n) double bed (a bed wide enough to accommodate two sleepers)
    - S: (n) four-poster (a bed with posts at the four corners that can be used to support a canopy or curtains)
    - S: (n) hammock, sack (a hanging bed of canvas or rope netting (usually suspended between two trees); swings easily)
    - S: (n) marriage bed (the bed shared by a newly wed couple)
    - S: (n) Murphy bed (a bed that can be folded or swung into a cabinet when not being used)
    - S: (n) plank-bed (a bed of boards (without a mattress))
    - S: (n) platform bed (a bed without springs)
    - S: (n) sickbed (the bed on which a sick person lies)
    - S: (n) single bed (a bed for one occupant)
    - S: (n) sleigh bed (a bed with solid headboard and footboard that roll outward at the top)
    - S: (n) trundle bed, trundle, truckle bed, truckle (a low bed to be slid under a higher bed)
    - S: (n) twin bed (one of a pair of identical beds)
    - S: (n) water bed (a bed with a mattress made of strong plastic that is filled with water)
  - *part meronym*
    - S: (n) bedstead, bedframe (the framework of a bed)
    - S: (n) mattress (a large thick pad filled with resilient material and often incorporating coiled springs, used as a bed or part of a bed)
  - *direct hypernym* / *inherited hypernym* / *sister term*
    - S: (n) bedroom furniture (furniture intended for use in a bedroom)

DBPEDIA

- Started in 2007.
  - Free University of Berlin, Leipzig University.
- RDF knowledge base extracted from Wikipedia :
  - Editions in 111 languages (English is largest).
  - SPARQL query access to 14 languages.
  - Global network of local DBpedia chapters.
  - 5.2 M entities in a consistent ontology (2016).
- Interlinking hub for the web of linked data :
  - Many Linked Data publishers use RDF links to DBpedia.
- From 2010, community-curated ontology :
  - With mappings from Wikipedia infobox properties.
  - Regular releases+ automatic updates of live KB.

(sources http://wiki.dbpedia.org/; Lehman et al. 2015)

Ford GT40

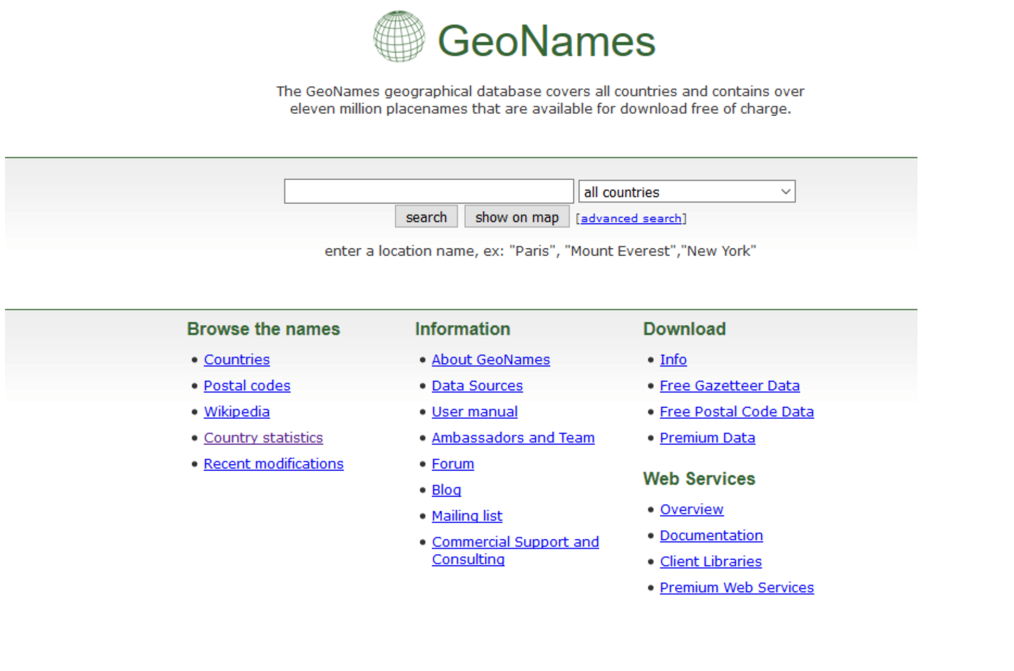
Overview	
Manufacturer	Ford Advanced Vehicles John Wyer Automotive Engineering Kar Kraft Shelby American
Production	1964-1969[1] 105 produced[2]
Assembly	Slough, UK (Mk I, Mk II, and Mk III) Wixom, Michigan, United States (Mk IV)
Body and chassis	
Class	Group 4 sports car Group 6 sports prototype
Body style	Coupé Roadster
Powertrain	
Engine	4181 cc (255 CID) V-8 4737 cc (289 CID) V-8 6997 cc (427 CID) V-8 4942 cc (302 CID) V-8
Transmission	5-speed manual
Dimensions	
Wheelbase	95 in (2,413 mm)[3]
Length	160 in (4,064 mm)
Width	70 in (1,778 mm)
Height	40.5 in (1,029 mm)
Curb weight	2,682 lb (1,217 kg) (1966, Mk IIA)[4]
Chronology	
Successor	Ford P68 (racing heritage) Ford GT (street heritage)

```
dbr:Ford_GT40
  rdf:type     dbo:Automobile;
  rdfs:label "Ford GT40"@en;
  dbo:manufacturer
               dbr:Ford_Advanced_Vehicles;
  dbo:productionStartYear
               "1964"^^xsd:gYear;
  dbo:productionEndYear "1969"^^xsd:gYear;
  dbo:engine [
               rdf:type AutomobileEngine;
               dbo:displacement "0.004181";
  ]
  (...) .
```

Geonames

- Widely used geographical database
  - Over 10 million geographical names and of over 9 million unique features.
  - Data is accessible free of charge through webservices and a daily database export.
  - Available in OWL.
- GeoNames is serving up to over 150 million web service requests per day.

(http://www.geonames.org/; http://geotree.geonames.org/)



Domain ontologies

- Examples of this chapter were focusing on general and upper ontologies.
- As seen in chapter 1, semantic data are also used in many application domains.
- Some of the related domain ontologies will be covered in chapters 9 and 11.

Summary

- An ontology is a formal specification of a shared conceptualization.
- Ontological commitment is an important decision in the design of knowledge-based agents, supporting common communication and reducing ambiguity.
- Hierarchization of ontologies into upper ontologies and domain ontologies increases opportunities for reuse.
- The upper ontology contains axioms defining reusable general knowledge.
  It typically covers general-purpose models (abstract and physical, objects and matter, events and processes, space and time, mereology and topology).
- Choosing an appropriate upper ontology and reusing its structure and axioms is an important step in designing an ontology, to avoid starting from scratch.
- A number of significant ontologies of practical use exist today.

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THANK YOU