Modelling challenges for OWL
Part-whole relations
The temporal dimension
Summary

Semantic Web Technologies
Lecture 6: Ontology engineering: parts, wholes, and time

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The landscape

- OWL 2 DL is quite expressive, but this does not mean one can represent everything
- Trade-offs between expressiveness and computational complexity
- One can choose for different combinations of the trade-offs
  - properties of the object properties
  - other operators
  - settle for ‘workarounds’ w.r.t. modelling
- For instance, parthood in its full glory, temporalizations, fuzzy, probabilistic

Examples

- SNOMED CT: “Concussion with loss of consciousness for less than one hour”, where the loss of consciousness still can be before or after the concussion
- Difference between how the brain and a heart are part of your body
- Classifying “ripe” apples or “the set of all individuals that mostly buy low calorie food"
- “Butterfly is a transformation of Caterpillar”
- The wall that is shared by the adjacent—overlaps with the—semi-detached houses
Some questions and problems (not exhaustive...)

- Is a tunnel part of the mountain?
- What is the difference, if any, between how Cell nucleus and Cell are related and how Receptor and Cell wall are related?
- And w.r.t. Brain part of Human and/or Hand part of Boxer? (assuming boxers must have their own hands)
- A classical example: hand is part of musician, musician part of orchestra, but clearly, the musician’s hands are not part of the orchestra. Is part-of then not transitive, or is there a problem with the example?

1The following slides are based on the tutorial given at Meraka [http://www.meteck.org/files/PartspresMOWS08.pdf], which does have the references to the related works.

Analysis of the issues from diverse angles

- Mereological theories (Varzi, 2004), usage & extensions (e.g. mereotopology, relation with granularity, set theory)
- Early attempts with direct parthood, SEP triples, and other outstanding issues, some still remaining
- Cognitive & linguistic issues from meronymy
- Usage in conceptual modelling and ontology engineering
- Subject domains: thus far, mainly geo, bio, medicine

Ground Mereology

Reflexivity (everything is part of itself)

\[ \forall x (\text{part} \_ \text{of}(x, x)) \] (1)

Antisymmetry (two distinct things cannot be part of each other, or: if they are, then they are the same thing)

\[ \forall x, y ((\text{part} \_ \text{of}(x, y) \wedge \text{part} \_ \text{of}(y, x)) \rightarrow x = y) \] (2)

Transitivity (if x is part of y and y is part of z, then x is part of z)

\[ \forall x, y, z ((\text{part} \_ \text{of}(x, y) \wedge \text{part} \_ \text{of}(y, z)) \rightarrow \text{part} \_ \text{of}(x, z)) \] (3)

Proper parthood

\[ \forall x, y (\text{proper} \_ \text{part} \_ \text{of}(x, y) \equiv \text{part} \_ \text{of}(x, y) \wedge \neg \text{part} \_ \text{of}(y, x)) \] (4)

Proper parthood

\[ \forall x, y (\text{proper} \_ \text{part} \_ \text{of}(x, y) \equiv \text{part} \_ \text{of}(x, y) \wedge \neg \text{part} \_ \text{of}(y, x)) \] (5)

Asymmetry (if x is part of y then y is not part of x)

\[ \forall x, y (\text{part} \_ \text{of}(x, y) \rightarrow \neg \text{part} \_ \text{of}(y, x)) \] (6)

Irreflexivity (x is not part of itself)

\[ \forall x (\neg \text{part} \_ \text{of}(x, x)) \] (7)
Defining other relations with **part_of**

**Overlap**  (x and y share a piece z)

\[ \forall x, y (\text{overlap}(x, y) \equiv \exists z (\text{part_of}(z, x) \land \text{part_of}(z, y))) \]  (8)

**Underlap**  (x and y are both part of some z)

\[ \forall x, y (\text{underlap}(x, y) \equiv \exists z (\text{part_of}(x, z) \land \text{part_of}(y, z))) \]  (9)

**Over-**  **& undercross**  (over/underlap but not part of)

\[ \forall x, y (\text{overcross}(x, y) \equiv \text{overlap}(x, y) \land \neg \text{part_of}(x, y)) \]  (10)

\[ \forall x, y (\text{undercross}(x, y) \equiv \text{underlap}(x, y) \land \neg \text{part_of}(x, y)) \]  (11)

**Proper overlap & Proper underlap**

\[ \forall x, y (\text{p_overlap}(x, y) \equiv \text{overcross}(x, y) \land \text{overcross}(y, x)) \]  (12)

\[ \forall x, y (\text{p_underlap}(x, y) \equiv \text{undercross}(x, y) \land \text{undercross}(y, x)) \]  (13)

### General Extensional Mereology

- **Strong supplementation** [EM]

  \[ \neg \text{part_of}(y, x) \rightarrow \exists z (\text{part_of}(z, y) \land \neg \text{overlap}(z, x)) \]  (14)

- And add unrestricted fusion [GEM]. Let \( \phi \) be a property or condition, then for every satisfied \( \phi \) there is an entity consisting of all entities that satisfy \( \phi \).\(^2\) Then:

  \[ \exists x \phi \rightarrow \exists z \forall y (\text{overlap}(y, z) \leftrightarrow \exists x (\phi \land \text{overlap}(y, x))) \]  (15)

- Note that in EM and upward we have identity, from which one can prove acyclicity for ppo

- There are more mereological theories, and the above is not uncontested (more about that later)

\(^2\)Need to refer to classes, but desire to stay within FOL. Solution: axiom schema with only predicates or open formulas

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### Relations between common mereological theories

- With \( x \) as part, what to do with the remainder that makes up \( y \)?
  - **Weak supplementation**: every proper part must be supplemented by another, disjoint, part. **MM**
  - **Strong supplementation**: if an object fails to include another among its parts, then there must be a remainder. **EM**

- Problem with EM: non-atomic objects with the same proper parts are identical, because of this (extensionality principle), but sameness of parts may not be sufficient for identity E.g.: two objects can be distinct purely based on arrangement of its parts, differences status and its marble (multiplicative approach)

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**Fig. 1**: Hasse diagram of mereological theories; from weaker to stronger, going uphill (after [44]).
Can any of this be represented in a decidable fragment of first order logic for use in ontologies and (scalable) software implementations?

Things are improving...

- Early days (90s) and simplest options: DL-role $R$ as part-of, or has-part added as primitive role as $\geq$, model it as the transitive closure of a parthood relation (16) and define e.g. Car as having wheels that in turn have tires (17):

  \[
  \geq \equiv (\text{primitive-part})^* \quad (16)
  \]

  \[
  \text{Car} \sqsubseteq \exists \geq (\text{Wheel} \sqcap \exists \geq \text{Tire}) \quad (17)
  \]

  Then Car $\sqsubseteq \exists \geq \text{Tire}$

- SEP triples with $\mathcal{ALC}$

- What $\mathcal{SHIQ}$ fixes cf. $\mathcal{ALC}$: Transitive roles, Inverse roles (to have both part-of and has-part), Role hierarchies (e.g. for subtypes of part-of), qualified Number restrictions (e.g. to represent that a bycicle has-part 2 wheels)

- Build-your-own DL-language

What we can(not) implement now with DL-based ontology languages

<table>
<thead>
<tr>
<th>Language</th>
<th>$\mathcal{DLR}_\mu$</th>
<th>SHOIN</th>
<th>$\mathcal{SROIQ}$</th>
<th>DL-LiteA</th>
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<td>Reflexivity $^*$</td>
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<td>Antisymmetry $^*$</td>
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<td>Transitivity $^*$ $^\dagger$</td>
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<td>Asymmetry $^\dagger$</td>
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<td>Irreflexivity $^\dagger$</td>
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<td>Acyclicity</td>
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Definitions in OBO Relations Ontology

- Instance-level relations
  - $c$ part-of $c_1$ at $t$ - a primitive relation between two continuant instances and a time at which the one is part of the other
  - $p$ part-of $p_1$, $r$ part-of $r_1$ - a primitive relation of parthood, holding independently of time, either between process instances (one a subprocess of the other), or between spatial regions (one a subregion of the other)
  - $c$ contained-in $c_1$ at $t$ $\equiv$ $c$ located-in $c_1$ at $t$ and not $c$ overlap $c_1$ at $t$
  - $c$ located-in $r$ at $t$ - a primitive relation between a continuant instance, a spatial region which it occupies, and a time
Definitions in OBO Relations Ontology

- **Class-level relations**
  - \( C \text{ part of } C_1 \) for all \( c, t \), if \( Cc_t \) then there is some \( c_1 \) such that \( C_1c_1t \) and \( c \text{ part of } c_1 \) at \( t \).
  - \( P \text{ part of } P_1 \) for all \( p \), if \( Pp \) then there is some \( p_1 \) such that: \( P_1p_1 \) and \( p \text{ part of } p_1 \).
  - \( C \text{ contained in } C_1 \) for all \( c, t \), if \( Cc_t \) then there is some \( c_1 \) such that: \( C_1c_1t \) and \( c \text{ contained in } c_1 \) at \( t \).

- **Need to commit to a foundational ontology.** Recently, linked to BFO http://obofoundry.org/ro/#mappings (test release)

- **Same labels, different relata and only a textual constraint:**
  
  *Label the relations differently*

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Linguistic use of part-whole relations (meronymy)

- **Part of?**
  - Centimeter part of Decimeter
  - Decimeter part of Meter
    
    *therefore* Centimeter part of Meter
  - Meter part of SI
    
    — but not Centimeter part of SI

- **Transitivity?**
  - Person part of Organisation
  - Organisation located in Bolzano
    
    *therefore* Person located in Bolzano?
  
    — but not Person part of Bolzano

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Linguistic use of part-whole relations

- **Which part of?**
  - CellMembrane structural part of RedBloodCell
  - RedBloodCell part of Blood
    
    — but not CellMembrane structural part of Blood
  - Receptor structural part of CellMembrane
    
    *therefore* Receptor structural part of RedBloodCell

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Linguistic use of part-whole relations

- Which part of?
  - CellMembrane structural part of RedBloodCell
  - RedBloodCell contained in? Blood
    - but not CellMembrane structural part of Blood
  - Receptor structural part of CellMembrane
    - therefore Receptor structural part of RedBloodCell

Addressing the issues

- Efforts to disambiguate this confusion; e.g. an informal taxonomy by Winston (1987), list of 6 types motivated by CMing (Odell) ontology-inspired conceptual modelling (Guizzardi)
- Location, containment, membership of a collective, quantities of a mass
- Relatively well-settled debate on transitivity, or not

Overview

- Mereological part_of (and subtypes) versus ‘other’ part-whole relations
- Categories of object types of the part-whole relation changes
- Structure these relations by (non/in)transitivity and kinds of relata
- Simplest mereological theory, $\mathbf{M}$.
- Commit to a foundational ontology: DOLCE (though one also could choose, a.o., BFO, OCHRE, GFO, …)
Part-whole relations

“member-bunch”, collective nouns (e.g. Herd, Orchestra) with their members (Sheep, Musician)

\[
\forall x, y \left( member\_of(x, y) \equiv mpart\_of(x, y) \land (POB(x) \lor SOB(x)) \land SOB(y) \right)
\]

“material-object”, that what something is made of (e.g., Vase and Clay)

\[
\forall x, y \left( constitutes_k(x, y) \equiv constituted\_of_k(y, x) \equiv mpart\_of(x, y) \land POB(y) \land M(x) \right)
\]

“quantity-mass”, “portion-object”, relating a smaller (or sub) part of an amount of matter to the whole. Two issues (glass of wine & bottle of wine vs. Salt as subquantity of SeaWater)

\[
\forall x, y \left( sub\_quantity\_of_n(x, y) \equiv mpart\_of(x, y) \land M(x) \land M(y) \right)
\]

“noun-feature/activity”, entity participates in a process, like Enzyme that participates in CatalyticReaction

\[
\forall x, y \left( participates\_in_k(x, y) \equiv mpart\_of(x, y) \land ED(x) \land PD(y) \right)
\]

processes and sub-processes (e.g. Chewing is involved in the grander process of Eating)

\[
\forall x, y \left( involved\_in(x, y) \equiv part\_of(x, y) \land PD(x) \land PD(y) \right)
\]

Object and its 2D or 3D region, such as contained\_in (John’s address book, John’s bag) and located\_in (Pretoria, South Africa)

\[
\forall x, y \left( contained\_in(x, y) \equiv part\_of(x, y) \land R(x) \land R(y) \land \exists z, w \left( has\_3D(z, x) \land has\_3D(w, y) \land ED(z) \land ED(w) \right) \right)
\]

\[
\forall x, y \left( located\_in(x, y) \equiv part\_of(x, y) \land R(x) \land R(y) \land \exists z, w \left( has\_2D(z, x) \land has\_2D(w, y) \land ED(z) \land ED(w) \right) \right)
\]

\[
\forall x, y \left( s\_part\_of(x, y) \equiv part\_of(x, y) \land ED(x) \land ED(y) \right)
\]
Using the taxonomy of part-whole relations

- Representing it correctly in ontologies and conceptual data models
- Reasoning with a taxonomy of relations

Decision diagram

- Does the part-of role relate roles?
  - Yes: X part-of Y → X involved-in Y
  - No: Is X a member of Y? (like player-team)
    - Yes: X part-of Y → X member-of Y
    - No: Is X made of Y? (like bike-steel, vase-clay)
      - Yes: X part-of Y → Y constituted-of X
      - No: Is X a portion or subquantity of Y? (like slice-pie, wine or other mass noun)
        - Yes: X part-of Y → X sub-quantity-of Y
        - No: X part-of Y → X s-part-of Y (structural part-of, like shelf-cupboard)

- Are X and Y geographical object types? (as in place-area, like Massif Central in France)
  - Yes: X part-of Y → X contained-in Y (like a book in the bag)
  - No: Is X part-of an event Y? (like bachelor-party, enzyme-reaction)
    - Yes: X part-of Y → X participates-in Y
    - No: Is X part-of an event Y? (like bachelor-party, enzyme-reaction)
      - Yes: X part-of Y → X participates-in Y
      - No: X part-of Y → X located-in Y

Decision diagram

- Is X a spatial part of Y? (like oasis-desert, nucleus-cell)
  - Yes: X part-of Y → X sub-quantity-of Y
  - No: Is X a spatial part of Y? (like oasis-desert, nucleus-cell)
    - Yes: X part-of Y → X sub-quantity-of Y
    - No: Is X a spatial part of Y? (like oasis-desert, nucleus-cell)
      - Yes: X part-of Y → X sub-quantity-of Y
      - No: Is X part-of an event Y? (like bachelor-party, enzyme-reaction)
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                    - Yes: X part-of Y → X participates-in Y
                    - No: Is X part-of an event Y? (like bachelor-party, enzyme-reaction)
Example - before

Example - after

Requirements

- Represent at least Ground Mereology,
- Express ontological categories and their taxonomic relations,
- Having the option to represent transitive and intransitive relations, and
- Specify the domain and range restrictions (/relata/entity types) for the classes participating in a relation.
Modelling challenges for OWL

Part-whole relations

The temporal dimension

Summary

Current behaviour of reasoners

A1. Class hierarchy with asserted conditions

B. Correct role box (object properties)

C. Wrong role box (object properties)

A2. Other class hierarchy with the same asserted conditions

The RBox Compatibility service – definitions

Definition (Domain and Range Concepts)

Let $R$ be a role and $R \subseteq C_1 \times C_2$ its associated Domain & Range axiom. Then, with the symbol $D_R$ we indicate the User-defined Domain of $R$—i.e., $D_R = C_1$—while with the symbol $R_R$ we indicate the User-defined Range of $R$—i.e., $R_R = C_2$.

Definition (RBox Compatibility)

For each pair of roles, $R, S$, such that $\langle T, R \rangle \models R \subseteq S$, check:

Test 1. $\langle T, R \rangle \models D_R \subseteq S$ and $\langle T, R \rangle \not\models R_R \subseteq R_S$;

Test 2. $\langle T, R \rangle \not\models D_S \subseteq R_D$;

Test 3. $\langle T, R \rangle \not\models R_S \subseteq R_R$.

An RBox is said to be compatible iff Test 1 and (2 or 3) hold for all pairs of role-subrole in the RBox.

The RBox Compatibility service – behaviour

- If Test 1 does not hold: warning that domain & range restrictions of either $R$ or $S$ are in conflict with the role hierarchy proposing either
  (i) To change the role hierarchy or
  (ii) To change domain & range restrictions or
  (iii) If the test on the domains fails, then propose a new axiom $R \sqsubseteq D'_R \times R_R$, where $D'_R \equiv D_R \sqcap D_S^3$, which subsequently has to go through the RBox compatibility service (and similarly when Test 1 fails on range restrictions).

$^3$The axiom $C_1 \equiv C_2$ is a shortcut for the axioms: $C_1 \subseteq C_2$ and $C_2 \subseteq C_1$. 

Current behaviour of reasoners

1. A1+B+racer: ontology OK

2. A2+B+racer: ontology OK

3. A1+C+racer: class hierarchy is inconsistent

4. A2+C+racer: Chassis reclassified as PD

Recover log

- Concepts
- FO

Computing superroles: Querying reasoner...
The RBox Compatibility service – behaviour

- If Test 2 and Test 3 fail: warn that R cannot be a proper subrole of S but that the two roles can be equivalent. Then, either:
  (a) Accept the possible equivalence between the two roles or
  (b) Change domain & range restrictions.
- Ignoring all warnings is allowed, too

Which kind of temporal things?

- Actual dates, time, intervals
- Qualitative temporal relations, such as: before, after, during, while, meet (Allen temporal relations)
- More advanced relations (that possibly can be dealt with with simpler ones): e.g., transformation_of, developed_from, derived_from
- Temporalising classes (cf. ‘object migration’ in databases)
- Temporalising relations; e.g. ‘during the lifetime of x, it always has y as part’

Examples

- Buttery is a transformation of Caterpillar, using both LTL and the phased sortals of OntoClean (Keet, 2009)
- Brain is specific dependent part of Human body, using temporalisation of the parthood relation (AGK 2008)
- Bypass sometimes comes after the grafting, using CTL then we have E[grafting U bypass]

  - Note shorthand CTL notations: E: exists a path; A: in all paths; F: some time in the future; G: globally in the future; X: next time; and U for p until q

Post-script: extensions in various directions

- Mereotopology, with location, GIS, Region Connection Calculus (http://www.comp.leeds.ac.uk/qsr/rcc.html)

  \[
  d_e(X,Y) \quad e_e(X,Y) \quad p_o(X,Y) \quad e_q(X,Y) \quad t_{pp}(X,Y) \quad t_{pp}\{X,Y\} \quad n_{pp}(X,Y) \quad n_{pp}\{X,Y\}
  \]

- Mereogeometry
- Mereology and vs granularity
- Temporalising the part-whole relations
Reasoning services

- The usual ones (satisfiability, subsumption, etc.)
- Querying temporal knowledge bases
  - “In which year in the previous century was the great flooding (watersnoodramp) in the Netherlands?”
  - “Who was the Italian prime minister before Berlusconi?”
- Logical implications; e.g. given \( B \subseteq A \), then
  - objects active in \( B \) must be active in \( A \) (e.g., if one is a student (\( B \)) then one is also a person (\( A \))),
  - objects scheduled to become active in \( B \) must exist in \( A \) (e.g., an employee (\( A \)) is up for promotion to become a manager (\( B \)))
- A range of other examples, a.o.:
  - Reasoning with a calendar hierarchy and across calendars
  - Finding a solution satisfying a set of constraints for scheduling the lecture hours of a study programme

Overview

- An ontology to describe the temporal content of Web pages and the temporal properties of Web services
- Vocabulary for expressing facts about topological relations among instants and intervals, together with information about durations, and about datetime information
- OWL encoding and a first-order logic axiomatization of the ontology
- It is an ontology to talk about time, but not to represent and reason over temporal knowledge, i.e., a ‘workaround’
  more info at http://www.w3.org/TR/owl-time/

Core: Topological Temporal Relations

- TemporalEntity with two subclasses Instant and Interval
- hasBeginning and hasEnd are relations between instants and temporal entities
- inside is a relation between an instant and an interval
- before relation on temporal entities, which gives directionality to time, but is not enforced in the language
- Interval relations, such as intervalEquals, intervalBefore, intervalMeets etc.

Core: Duration Description

- An interval can have multiple duration descriptions (e.g., 2 days, 48 hours), but can only have one duration
- Different sets of properties for DateTimeDescription and DurationDescription, because their ranges are different.
  - year (in DateTimeDescription) has a range of xsd:gYear, while years (in DurationDescription) has a range of xsd:decimal so that you can say duration of 2.5 years.
- durationOf that takes eight arguments, but split up into 8 binaries
- Other components: Time Zones, DateTime Description
Modelling challenges for OWL

Part-whole relations
- Parts, mereology, meronymy
- Taxonomy of types of part-whole relations
- Using the taxonomy of part-whole relations

The temporal dimension
- Identifying temporal aspects
- Time Ontology