Semantic Theory:
Lexical Semantics III

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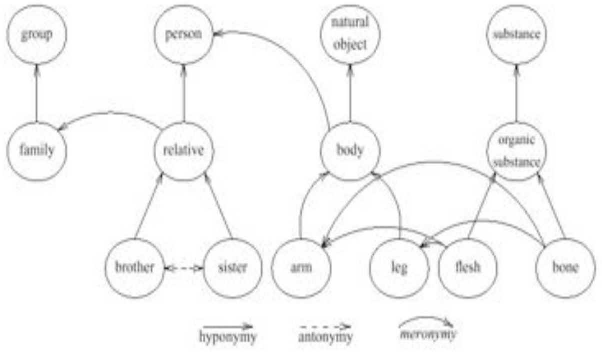
WordNet Again

Figure 2. Network representation of three semantic relations among an illustrative variety of lexical concepts



WordNet Relations in FOL

... and in Description Logic

$\forall x(\text{family}(x) \rightarrow \text{group}(x))$

$\text{family} \sqsubseteq \text{group}$

$\forall x(\text{relative}(x) \rightarrow \text{person}(x))$

$\text{relative} \sqsubseteq \text{person}$

$\forall x(\text{person}(x) \rightarrow \exists y(\text{substance\_m}(y,x) \wedge \text{body}(y))$

$\text{person} \sqsubseteq \exists \text{substance\_m.body}$

$\forall x(\text{body}(x) \rightarrow \exists y(\text{part\_m}(y,x) \wedge \text{leg}(y))$

$\text{body} \sqsubseteq \exists \text{part\_m.leg}$

WordNet Relations in Description Logic

$\text{Body} \sqsubseteq \text{Natural\_object}$
$\text{Relative} \sqsubseteq \text{Person}$
$\text{Sister} \sqsubseteq \text{Relative}$
$\text{Bone} \sqsubseteq \text{Organic\_substance}$

$\text{Arm} \sqsubseteq \exists \text{Substance\_m.Flesh}$
$\text{Body} \sqsubseteq \exists \text{Part\_m.Arm}$
$\text{Person} \sqsubseteq \exists \text{Substance\_m.Body}$

$\text{Family} \sqsubseteq \text{Group}$
$\text{Brother} \sqsubseteq \text{Relative}$
$\text{Flesh} \sqsubseteq \text{Organic\_substance}$
$\text{Organic\_substance} \sqsubseteq \text{Substance}$

$\text{Arm} \sqsubseteq \exists \text{Substance\_m.Bone}$
$\text{Body} \sqsubseteq \exists \text{Part\_m.Leg}$
$\text{Relative} \sqsubseteq \exists \text{Member\_m.Family}$

Description Logic: Terms

Atomic Concepts:

- Concepts A ≈ unary predicates in FOL
- Empty and universal concept: $\bot$, $\top$
- Roles R ≈ binary relations in FOL

Complex concepts:

- Conjunction and disjunction of concepts: $C1 \sqcap C2$, $C1 \sqcup C2$
- Negation (complementary concept): $\neg C$
- Existential restriction: $\exists R.C$
  (“something that has an R which is a C”)
- Value restriction: $\forall R.C$
  (“something all of whose R’s (if any) are C”)
- Number or Cardinality Restrictions: $\exists_{\leq m}R$/ $\exists_{\geq m}R$/ $\exists_{=m}R$
  (“Something that has at most/ at least/ exactly m different Rs”)

Formulas in Description Logic

- Axioms or Rules encode terminological knowledge
  - Inclusion $C \sqsubseteq D$, $R \sqsubseteq S$
  - Equality $C \equiv D$, $R \equiv S$
  - If the first concept of an equality axiom is atomic, the axiom is called a definition.
- Axioms form the „TBox“, containing the conceptual knowledge

bachelor $\equiv \neg \exists$married.$\top \sqcap$ man	*„bachelors are unmarried men“*
married $\equiv$ married^{-1}	(being married to so. is reflexive)
$\exists$ married.$\top \sqsubseteq$ happy	*„all married people are happy“*
$\exists_{\geq 2}$ love $\sqsubseteq \bot$	*„you can love at most one person“*
$\exists$ married.woman $\sqsubseteq \exists$ love.woman	*„someone married to a woman is someone who loves a woman“*

Formulas in Description Logic

- Assertions encode world knowledge:
  - C(a), R(a,b)
    where C and R are TBox concepts and roles,
    a, b, c, … are individual constants
- A set of assertions forms the „ABox“

woman(mary)
man(sam)
loves(john,mary)
married(sam,sue)
man(john)
woman(sue)
loves(mary,sam)
happy(sam)

An example

A T-BOX

bachelor $\equiv \neg \exists$married.$\top \sqcap$ man	*„bachelors are unmarried men“*
married $\equiv$ married^{-1}	(being married to so. is reflexive)
$\exists$ married.$\top \sqsubseteq$ happy	*„all married people are happy“*
$\exists_{\geq 2}$ love $\sqsubseteq \bot$	*„you can love at most one person“*
$\exists$ married.woman $\sqsubseteq \exists$ love.woman	*„someone married to a woman is someone who loves a woman“*

An A-BOX

woman(mary)
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happy(sam)

Model-theoretic Interpretation

- Like FOL model structure:
  - $M = \langle D, I \rangle$ (notational variant of $\langle U, V \rangle$)
  - D is domain of individuals
  - I is interpretation function, providing DL expressions with appropriate value

- Interpretation of concepts, roles, and individual constants:
  - $I(A) \subseteq D$ for atomic concepts A
  - $I(R) \subseteq D \times D$ for roles R
  - $I(a) \in D$ for individual constants a

  - $I(\bot) = \varnothing$
  - $I(\top) = D$

  - $I(C \sqcap D) = I(C) \cap I(D)$
  - $I(C \sqcup D) = I(C) \cup I(D)$
  - $I(\neg C) = D \backslash I(C)$
  - $I(\exists R.C) = \{a \in D \mid$ there is b with $\langle a,b \rangle \in I(R)$ and $b \in I(C)\}$
  - $I(\exists R.C) = \{a \in D \mid$ for all b with $\langle a,b \rangle \in I(R)$: $b \in I(C)\}$

Model-theoretic Interpretation

- Interpretation of formulas (axioms and assertions):
  - $I(C \sqsubseteq D) = 1$ iff $I(C) \subseteq I(D)$
  - $I(C \equiv D) = 1$ iff $I(C) = I(D)$

  - $I(C(a)) = 1$ iff $I(a) \in I(C)$
  - $I(R(a, b)) = 1$ iff $\langle I(a), I(b) \rangle \in I(R)$

Some Facts about Description Logic

- All versions of description logic are proper FOL fragments.
- Major reasoning tasks in description logic:
  - Subsumption check (Is C sub-concept of D? - Inheritance!)
  - Satisfiability check (Are C and D compatible?)
- DL reasoning is much more efficient than FOL deduction.
- There are different versions of description logic, including or exluding, e.g., full term negation, union, number restrictions.
- Trade-off between expressive power and computational complexity
- DL reasoners: FaCT, Racer, Protégé, supporting different reasoning tasks for different DL versions.
- Description Logics form the core or backbone of Semantic Markup Languages for the Web (e.g., OWL) and various ontologies

Ontologies

- An ontology is a shared conceptualization of a domain
- An ontology is a set of definitions in a formal language for terms describing the world

  (Definition taken from slides of Adam Pease)

- Another definition: Ontologies are
  - Hierarchical data structures
  - Providing formally rigorous information about concepts and relation
  - Within a specific domain (domain ontologies)
  - Or concepts and relations of foundational, domain-independent relevance (upper ontologies)
- Upper Ontologies:
  - DOLCE, CYC, SUMO

Event Semantics: Donald Davidson's Problem

(1) *The gardener killed the baron at midnight in the park*

$\Rightarrow$ $kill_4(g, b, m, p)$

(2) *The gardener killed the baron at midnight*

$\Rightarrow$ $kill_3(g, b, m)$

(3) *The gardener killed the baron in the park*

$\Rightarrow$ $kill_2(g, b, p)$

(4) *The gardener killed the baron*

$\Rightarrow$ $kill_1(g, b)$

A Problem

- Problem: How can the logical entailment relations between the different uses of *kill* be systematically explained?

$$\begin{tikzcd}
& (1) \arrow[dl, phantom, sloped, "\models"] \arrow[dr, phantom, sloped, "\models"] & \\
(2) \arrow[dr, phantom, sloped, "\models"] & & (3) \arrow[dl, phantom, sloped, "\models"] \\
& (4) &
\end{tikzcd}$$

- Naïve FOL interpretation does not solve the problem:
  - $kill_4(g, b, m, p) \not\models kill_3(g, b, m)$
  - $kill_3(g, b, m) \not\models kill_1(g, b)$
  - etc.

Adjunct Interpretation: Second Attempt

- Precompute the maximum arity of the underlying predicate, as a fixed number.
- Bind syntactically unrealized argument positions with existential quantifier.

(1) $\Rightarrow$ $kill(g, b, m, p)$

(2) $\Rightarrow$ $\exists y\, kill(g, b, m, y)$

(3) $\Rightarrow$ $\exists x\, kill(g, b, x, p)$

(4) $\Rightarrow$ $\exists x \exists y\, kill(g, b, x, y)$

Another Problem

- What is the correct arity of an event verb/ its underlying predicate?

The gardener killed the baron at midnight in the park under cover of absolute darkness with a shotgun …

Adjunct Interpretation: Third Attempt

- Model adjuncts in type theory as higher-order operators, i.e., as sentence modifiers (type <t,t>):

  $(1) \Rightarrow \text{in the park}(\text{at-midight}(\text{kill}(g, b)))$
- The arity problem is solved: An arbitrary number of adjuncts can be iteratively applied, leaving the type of the resulting expression (t) unchanged
- However: The systematic entailment information is lost again:

  $\text{at-midnight}(\text{kill}(g, b)) \not\models \text{kill}(g, b)$

Davidson's Solution

- Verbs expressing events have an additional event argument, which is not realised at linguistic surface:

  kill $\Rightarrow \lambda x \lambda y \lambda e.\text{kill}(e,x,y)$, where kill: <e,<e,<e,t>>>
- Generally, event verbs are represented by relations of a fixed arity (number of syntactic complements +1)
- Adjuncts express two-place relations between events and the respective "cirumstantial information" (a time, a location, ...)
- The event variable is existentially bound:

  The gardener killed the baron at midnight in the park

  $\Rightarrow \exists e[\, \text{kill}(e,g,b) \wedge \text{time}(e, m) \wedge \text{location}(e, p) \,]$
- Event semantics permits an arbitrary number of adjunct, entailment from sentence with adjunct to sentence without adjunct follows trivially:

  $\exists e[\, \text{kill}(e,g,b) \wedge \text{time}(e, m) \wedge \text{location}(e, p) \,]$

  $\models \exists e[\, \text{kill}(e,g,b) \wedge \text{time}(e, m) \,]$

  $\models \exists e[\, \text{kill}(e,g,b) \,]$
- Note also: Verb semantics with events is much more intuitive.

Compositional Event Semantics

- Problem: How are event semantic representations compositionally derived?
- Remember intersective adjectives:
  - Adjectives in attributive use are common noun modifiers (type: <<e,t>,<e,t>>)
  - The intersective semantics adjectives like *red* is modelled by its analysis as

    red $\Rightarrow \lambda F \lambda x[F(x) \wedge \text{red}(x)]$
- Accordingly, adjuncts are analysed as intersective modifiers for event predicates:
  - *at midnight* $\Rightarrow \lambda E \lambda e[E(e) \wedge \text{time}(e, \text{midnight})]$
- *The gardener killed the baron at midnight*

  $\Rightarrow \lambda E \lambda e[E(e) \wedge \text{time}(e, \text{midnight})](\lambda e.\text{kill}(e, g, b))$

  $\Leftrightarrow \lambda e.\text{kill}(e, g, b) \wedge \text{time}(e, \text{midnight})$
- In finite/tensed clauses, the event variable is eventually bound:

  $\Rightarrow \exists e[\text{kill}(e, g, b) \wedge \text{time}(e, \text{midnight})]$

Uniform treatment of modifiers

- One semantic representation for PP modifiers used as adjuncts and in NO modification:

  in the park $\Rightarrow \lambda F \lambda x[F(x) \wedge \text{location}(x, p)]$
- Local adjunct as event modifier:

  [[The gardener killed the baron] in the park]
- Post-nominal modifier of an standard common noun:

  The [[pavillon] in the park]
- Event semantics provides a natural interpretation for deverbal common nouns and their modifiers:

  The [[murder] in the park]

Event Semantics and Thematic Roles

- Complements can be treated like adjuncts:
  - Represent event verbs as one-place event predicates.
  - Thematic roles as two-place relations linking arguments to the event denoted by the verb.

  The gardener killed the baron at midnight in the park

  $\Rightarrow \exists e\,[kill(e) \wedge ag(e,g) \wedge pat(e,b) \wedge time(e,m) \wedge location(e,p)]$

  or, using FrameNet frames and roles:

  $\exists e\,[killing(e) \wedge killer(e,g) \wedge victim(e,b)]$
- „Neo-Davidsonian“ semantics allows the partioning of semantic information into minimal pieces pieces of information: One-place and two-place predications.

Model theoretic semantics with events

- Model structure like in standard FOL, except that the universe is subdivided into
  - a set of standard individuals U_S
  - a set of events U_E
  - $M = \langle U, V\rangle$, $U = U_S \cup U_E$, $U_S \cap U_E = \varnothing$

Event anaphora in DRT

- Events as a new kind of individuals help also to give discourse semantics wider coverage:

- *The gardener killed the baron . It happened at midnight.*
- *Yesterday, I went by train from Hamburg to Saarbrücken. That was a boring trip.*

- Event referents
  - a new kind of discourse referents
  - are typically introduced by finite/ tensed clauses
  - can be referred to by nominal anaphoric expressions

Event anaphora in DRT

- *The gardener killed the baron . It happened at midnight.*

e, g, b	e, g, b,e'
gardener(g) baron(b) kill(e,g,b)	gardener(g) baron(b) kill(e,g,b) midnight(m) time(e',m) e'=e

Model theoretic semantics with events

- Model structure like in standard FOL, except that the universe is subdivided into
  - a set of standard individuals U_S, and
  - a set of events U_E
  - which is partially ordered by a "temporally precedes" relation.

Temporal relations in Event Semantics

- Event Semantics allows the explicit representation of tense and temporal relations in FOL/DRT

  John left $\Rightarrow \exists e[\, leave(e, j^*) \wedge e < e_u \,]$

  where < is interpreted as temporal precedence, and is the utterance event.

  John left, after Peter had arrived

  $\Rightarrow \exists e_1 \exists e_2[\, leave(e_1, j^*) \wedge e_1 < e_u \wedge arrive(e_2, p) \wedge e_2 < e_1 \,]$

Temporal relations in an Event Semantics

John left, after Peter had arrived

j, e, p, e'

leave(e,j)
$e < e_u$

arrive(e',p)
$e' < e$