Integrated Semantics for OWL Ontologies

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Example: OWL ontology O_1

```
Class(a:Adult partial)
Class(a:American complete
  restriction(a:livesIn value (a:US)))
Class(a:Country partial)
Class(a:Exception partial)
Class(a:CarOwner complete
 intersectionOf(complementOf(a:Exception) a:American a:Adult))
ObjectProperty(a:livesIn Functional range(a:Country))
Individual(a:John type(a:Adult) value(a:livesIn a:US))
Individual(a:US type(a:Country))
```

Infered type (Protege + Racer) CarOwner $= \emptyset$

Example: O_1 as a LP with NAF semantics

```
country(us) .
livesIn(john, us) .
adult(john) .
livesIn(nick, us) .
exception(peter) .  %just for defining the predicate exception
american(X) :- livesIn(X, us) .
carOwner(X) :- american(X), adult(X), \+ exception(X) .
```

Ciao execution:

```
?- carOwner(X) .
X = john ?
yes
```

Example: OWL ontology O_2

```
ObjectProperty(a:knownBy domain(a:foo) range(a:foo))

Class(a:famous complete
  restriction(a:knownBy someValuesFrom(complementOf(a:famous))
Class(a:foo partial  a:famous)

Individual(a:boby  type(a:foo)  value(a:knownBy a:john))
Individual(a:john  type(a:foo)  value(a:knownBy a:boby))
Individual(a:peter type(a:foo)  value(a:knownBy a:john)
                                value(a:knownBy a:boby))
```

Infered type (Protege + Racer) `famous` $= \emptyset$

Example: O_2 as a LP (NAF semantics)

```
foo(john) .
foo(boby) .
fooPerson(peter) .
knownBy(john, boby) .
knownBy(boby, john) .
knownBy(peter, john) .
knownBy(peter, boby) .
famous(X) :- knownBy(X, Y), \+famous(Y) .
```

Ciao execution:

```
?- famous(X) .
% Malloc: No such file or directory
ERROR: Memory allocated out of addressable bounds!
ERROR: segmentation violation
```

Example: O_2 as a LP (stable semantics)

AnsProlog:

```
Answer: 1
famous(peter)
famous(boby)
knownBy(peter,boby)
knownBy(peter,john)
knownBy(boby,john)
knownBy(john,boby)
foo(peter)
foo(boby)
foo(john)
```

```
Answer: 2
famous(peter)
famous(john)
knownBy(peter,boby)
knownBy(peter,john)
knownBy(boby,john)
knownBy(john,boby)
foo(peter)
foo(boby)
foo(john)
```

$\vdash$ famous(peter)

Example: O_2 as a LP (stable semantics)

AnsProlog:

```
Answer: 1
famous(peter)
famous(boby)
knownBy(peter,boby)
knownBy(peter,john)
knownBy(boby,john)
knownBy(john,boby)
foo(peter)
foo(boby)
foo(john)
```

```
Answer: 2
famous(peter)
famous(john)
knownBy(peter,boby)
knownBy(peter,john)
knownBy(boby,john)
knownBy(john,boby)
foo(peter)
foo(boby)
foo(john)
```

$\vdash$ famous(peter)

Example: remarks

- OWL semantics interpret ontologies under Open World Assumption (OWA): $O \models \neg\varphi$ iff all O-models interpret φ as being false
  $O \models$ `CarOwner(John)` iff `John` $\notin$ `Exception` in all O-models
- LP semantics interpret ontologies under Closed World Assumption (CWA): $O \models \neg\varphi$ iff NOT $O \vdash \varphi$
- various LP semantics interpret some OWL ontologies (e.g., O_1) in the same way, others (e.g., O_2) in a diffrent way. Why?
- O_1: NAF semantics = stable semantics
- O_2: NAF semantics $\neq$ stable semantics (`knownBy` is cyclic)
- When we believe an LP-based agent? (Is John a CarOwner?)
- How closing semantics can be expressed in OWL terms?

Example: remarks

We are able to answer the previous questions if we know

- what is a logic
- what is the logic corresponding to the interpretation under CWA
- what means a translation between two logics
  OWA - OWA
  OWA -CWA
- how to use modal operators to close semantics

What is a logic?

A possible answer is given by institutions (Goguen & Burstall, 1984)

- a collection of signatures: vocabularies
- a collection of models: structures interpreting the symbols (names) from a signature
- a collection of sentences: formulas built with symbols from a signature intended to express specific properties
- a satisfaction relation: says when a given sentence holds in a given model (both corresponding to the same signature)

Institution of Description Logic (DL)

- a signature consists of
  class names: CN $= \{$Country, American,$\ldots\}$
  property names: PN $=\{$livesIn$\}$
  individual names: IN $= \{$John$\}$
- morphism of signatures $\phi : \Sigma \to \Sigma'$
  class names $\to$ class names (e.g., ϕ(American)=AmericanCitizen
  property names $\to$ property names (e.g., ϕ(livesIn)=hasResidence
  individual names $\to$ individual names (e.g., ϕ(John)=JohnWalker

DL Institution

- a model consists of
  a carrier set Δ, e.g., *Reals*
  a class name is interpreted as a subset of Δ,
  e.g. $[\![Country]\!]$ = Integers, $[\![American]\!]$ = Irational numbers
  a property name is interpreted as a set of pairs, e.g.,
  $[\![livesIn]\!] = \{(x, [x]) \mid x \notin \mathrm{Integers}\}$
  an individual name is interpreted as an element of Δ,,
  e.g. $[\![John]\!] = 3.1415\ldots$
- model morphisms $h : M \to M'$, e.g., h : Reals $\to$ Complex
  (perhaps is difficult to find a morphism between Reals and People $\cup$ Countries)
- if $\phi : \Sigma \to \Sigma'$ and M' is a Σ'-model, then we can define the Σ-model $M'\restriction_{\phi}$, which is M' viewed as a Σ-model

Remark: It is more realistic for OWL to restrict the interpretation to Herbrand models; OWA is preserved (Fitting,1996).

DL Institution

- sentences express relations between class/properties expressions, e.g., $\forall\,\text{livesIn}.\{\text{US}\} \sqsubseteq \text{American}$
- signature morphisms are extended to sentence translations, e.g., $\phi(\forall\,\text{livesIn}.\{\text{US}\} \sqsubseteq \text{American}) =$ $\forall\,\text{hasResidence}.\{\text{USCountry}\} \sqsubseteq \text{AmericanCitizen}$
- satisfaction relation $M \models_\Sigma \forall\,\text{livesIn}.\{\text{US}\} \sqsubseteq \text{American}$
  it must satisfy the satisfaction condition:
  $M' \models_{\Sigma'} \forall\,\text{hasResidence}.\{\text{USCountry}\} \sqsubseteq \text{AmericanCitizen}$ iff
  $M'\restriction_\phi \models_\Sigma \forall\,\text{livesIn}.\{\text{US}\} \sqsubseteq \text{American}$
  the truth is invariant under change of notation

What is a Logic Morphism?

- institution morphisms - how a richer logic is built over a poorer one, e.g., $(\Phi, \beta, \alpha) : \mathsf{FOL} \to \mathsf{HL}$
- institution comorphisms - how a logic is encoded in another logic $(\Phi, \beta, \alpha) : \mathsf{DL} \to \mathsf{FOL}$
  Φ encodes DL signatures into FOL signatures
  β interpret FOL $\Phi(\Sigma)$-models as DL Σ-models
  α translates DL Σ-sentences into FOL $\Phi(\Sigma)$-sentences
- a satisfaction condition must be satisfied: a FOL M' model satisfies $\alpha(\varphi)$ iff the DL model $\beta(M')$ satisfies φ

The Institution of Logic Programming Paradigm

the signatures are logic programs (GHL specifications), e.g., P_1:

$$american(X) \leftarrow livesIn(X, us).$$
$$carOwner(X) \leftarrow american(X), adult(X), \textbf{not } Exception(X).$$

$$country(us).$$
$$livesIn(john, us).$$
$$adult(john).$$

GLP$^\bullet$ Institution

An LP paradigm associates a set of models $SEM(P)$ to a logic program P
E.g., stable semantics associates to P_1 the uniques stable model M_1:

```
Answer: 1
carOwner(john)
adult(john)
american(john)
livesIn(john,us)
country(us)
```

$P_1 \models^{STAB} \mathtt{carOwner}(\mathtt{john})$ and hence any model in $\underline{\widehat{\mathrm{GLP}}}^{STAB}$ must satisfy $\mathtt{carOwner}(\mathtt{john})$.

GLP• Institution

Let P_2 denote the logic program $P_1 \cup \{exception(john)\}$. P_2 has also a unique stable model, denoted by M_2:

```
Answer: 1
exception(john)
adult(john)
american(john)
livesIn(john,us)
country(us)
```

M_2 is not a model of P_1 in the sense of the stable semantics and therefore the inclusion $P_1 \subset P_2$ is NOT a signature morphism in $\widehat{\mathrm{GLP}}^{STAB}$.

GLP$^\bullet$ Institution

If we consider the program $P_3 = P_1 \cup \{american(peter)\}$, then its stable model is $M_3 = M_1 \cup \{\texttt{american}(\texttt{peter})\}$, which is a consistent extension of M_1 and therefore can be seen as a model for P_1

The functor $\mathrm{Mod}(\widehat{\underline{\mathrm{GLP}}}^\bullet)$ associates to a program those extended Herbrand models which are consistent extensions of models given by $SEM^\bullet$ (the Hebrand universe is extended with an infinite set of constants).

A FOL morphism $\phi : P \to P'$ is a signature morphism in $\widehat{\underline{\mathrm{GLP}}}^\bullet$ if and only if for each P'-model $M' \in \mathrm{Mod}^\bullet(P')$, its reduct $M'\restriction_\phi$ is a P-model.

In this the satisfaction condition is automatically satisfied.

Translation of DL in GLP•

Let KB_1 be the following DL knowledge base (DL semantics of O_1):

$$\begin{array}{l} Country \sqsubseteq \top \\ Adult \sqsubseteq \top \\ Exception \sqsubseteq \top \\ American \equiv \exists\, livesIn.\{US\} \\ Adult \sqcap American \sqcap (\neg\, Exception) \sqsubseteq carOwner \end{array}$$

$$\begin{array}{l} John \in adult \\ US \in country \\ \langle John, US \rangle \in livesIn \end{array}$$

KB_1 can be translated into logic program P_1.

We have $P_1 \models^{STAB} \texttt{carOwner(john)}$ but $KB_1 \not\models^{DL} John \in CarOwner$

Translation of DL in GLP•

$KB_2 = KB_1 \cup \{john \in exception\}$
P_2 is a translation of the KB_2 as a logic program.
$KB_1 \subset KB_2$ is a signature morphism in $\widehat{\underline{\mathrm{DL}}}^{th}$
but the inclusion $P_1 \subset P_2$ is not a morphism in $\widehat{\underline{\mathrm{GLP}}}^{STAB}$.

Therefore we consider a subinstitution $\widehat{\underline{\mathrm{DL}}}^{th,STAB}$, where only translatable morphisms are kept.

We can define now a comorphim $(\Phi, \beta, \alpha) : \widehat{\underline{\mathrm{DL}}}^{th,STAB} \to \widehat{\underline{\mathrm{GLP}}}^{STAB}$.

Integrated semantics

For the OWL ontology O_1 we have two semantics:

DL semantics (KB_1)

$\mathrm{GLP}^{\mathrm{STAB}}$ semantics (P_1)

Consider again $(\Phi, \beta, \alpha) : \widehat{\underline{\mathrm{DL}}}^{th,STAB} \to \widehat{\underline{\mathrm{GLP}}}^{STAB}$.

Since $\mathrm{Mod}(\widehat{\underline{\mathrm{GLP}}}^{STAB})(\Phi(KB_1) = P_1) \subset \mathrm{Mod}(\widehat{\underline{\mathrm{DL}}}^{th,STAB})(KB_1)$, the above comorphism close the semantics of DL according to stable semantics of LP

Can the two semantics live happily together into an integrated semantics for OWL?

Integrated semantics

Consider the diadram:

$$\underline{\widehat{\mathrm{DL}}}^{th} \underline{\widehat{\mathrm{DL}}}^{th,STAB} \underline{\widehat{\mathrm{GLP}}}^{STAB}$$

Let $\widehat{\mathrm{OWL}}^{D}$ be the semi-institution consisting of a pair $(\mathrm{Sign}(OWL^{D}), \mathrm{sen}(OWL^{D}))$, where $\mathrm{Sign}(OWL^{D})$ is subcategory of OWL ontologies which can be translated in signatures in $\underline{\widehat{\mathbb{I}}}$, for all $\underline{\widehat{\mathbb{I}}} \in |D|$

An interpretation $i(\underline{\widehat{\mathbb{I}}}) : \widehat{\mathrm{OWL}}^{D} \to \underline{\widehat{\mathbb{I}}}$ is a pair (Φ, α) defined in the same way as for inctitution comorphisms.

An O-model in $\mathrm{Mod}(\underline{\widehat{\mathrm{OWL}}}^{D})(O)$ is a pair (i, M), where $i = (\Phi, \alpha) : \widehat{\mathrm{OWL}}^{D} \to \underline{\widehat{\mathbb{I}}}$ is a interpretation and M is a $\Phi(O)$-model in $\underline{\widehat{\mathbb{I}}}$.

We have a model O-morphism $h : (i, M) \to (i', M')$ if and only if $i = (\Phi, \alpha) : \widehat{\mathrm{OWL}}^{D} \to \underline{\widehat{\mathbb{I}}}$, $i' = (\Phi', \alpha') : \widehat{\mathrm{OWL}}^{D} \to \underline{\widehat{\mathbb{I}}'}$, and there is a comorphism $(\underline{\Phi}, \underline{\beta}, \underline{\alpha}) : \underline{\widehat{\mathbb{I}}} \to \underline{\widehat{\mathbb{I}}'}$ such that $\underline{\beta}(M') = M$.

Closing Semantics = Hybrid Knowledge bases

A DL-based agent may interoperate with a GLP$^\bullet$-based agent only if their models are related by the functor $\underline{\beta}$.

Can $\underline{\beta}$ be syntactically represented? If yes, then it can be handled in SW.

The answer `carOwner(john)` given by P_1 must be read as "assuming that John is not an Exception, knowing that John is American, and knowing that John is an Adult, then we know that John is a CarOwner.

This can be expressed by the following MKNF rule:

$$\mathbf{K}\ carOwner(X) \leftarrow \mathbf{K}\ american(X), \mathbf{K}\ adult(X), \mathbf{not}\ Exception(X) \quad (1)$$

where $\mathbf{K}\ A$ is read as "A is known to hold" and $\mathbf{not}\ A$ as "is it possible for A not to hold".

Closing Semantics = Hybrid Knowledge bases

So, endowing O_1 with a $\mathrm{GLP}^{\mathrm{STAB}}$ semantics, we get back O_1 together with the constraint given by rule (1)

OWL DL ontologies together MKNF rule = Hybrid MKNF knowledge bases (Motik & Rosati, 2006)

$$\underline{\beta}(\mathrm{Mod}(\underline{\widehat{\mathrm{GLP}}}^{STAB})(P_1)) = \mathrm{Mod}(\underline{\widehat{\mathrm{HMKNFKB}}})(O_1, \{(1)\}).$$

I.e., O_1 toghethere with LP stable models is semantically equivalent with the hybrid MKNF kb consisting of O_1 and the rule (1)

Conclusion

- OWL ontologies can be interpreted using various logics
- ontology morphisms must also be taken into account
- different interpretations are related via comorphisms and together supplies an integrated semantics for OWL ontologies
- the DL reflection of an OWL DL ontology with LP stable semantics is equivalent with an hybrid MKNF knowledge base
- this result can be extended to other logics interpreting OWL under CWA (not only LP)
- integrated semantics can be enriched using limits/colimits

Thanks!