

Semantic Web Technologies

OWL DL and RDF Rules

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4 April 2007

Outline

OWL in RDF

Mapping OWL DL to RDF

Reasoning with OWL

RDF-based Rule Reasoning

DL-based Reasoning

OWL DL and Logic Programming

Description Logic Programs

Beyond DLP

OWL Lite/DL vs. RDF

- ▶ RDF Graph defined through translation from Abstract Syntax
- ▶ Example:

```
Class(Human partial Animal
      restriction(hasLegs cardinality(2))
      restriction(hasName allValuesFrom(xsd:string)))
```

Human	rdf:type	owl:Class
Human	rdfs:subClassOf	Animal
Human	rdfs:subClassOf	_:X1
_:X1	rdf:type	owl:Restriction
_:X1	owl:onProperty	hasLegs
_:X1	owl:cardinality	"2" xsd:nonNegativeInteger
Human	rdfs:subClassOf	_:X2
_:X2	rdf:type	owl:Restriction
_:X2	owl:onProperty	hasName
_:X2	owl:allValuesFrom	xsd:string

OWL Lite/DL vs. RDF

- ▶ Not every RDF graph is OWL Lite/DL ontology
- ▶ Example:

A rdf:type **A**

- ▶ How to check whether an RDF graph **G** is OWL DL?
 1. Construct an OWL ontology **O** in Abstract Syntax
 2. Translate to RDF graph **G'**
 3. If **G=G'**, then **G** is OWL DL
 - ▶ Otherwise, go to step (1)

OWL DL in RDF

- ▶ Mapping from OWL Abstract Syntax to RDF Graphs: given OWL ontology O , return RDF graph $T(O)$
- ▶ OWL DL
- ▶ Reuses RDF(S) vocabulary as much as possible
e.g. `rdfs:subClassOf`, `rdf:type`
- ▶ Complete translation online at:
<http://www.w3.org/TR/owl-semantics/mapping.html>
- ▶ We skip annotations here

Translating Ontologies

Abstract Syntax

Ontology(O $axiom_1$... $axiom_n$)

RDF graph

```
O rdf:type owl:Ontology .
```

```
T(axiom1) ... T(axiomn)
```

In case O is not present, a blank node is introduced.

Translating partial Class definition

Abstract Syntax

Class(classID partial *description*₁ ... *description*_n)

RDF graph

```
classID rdf:type owl:Class .
```

```
classID rdfs:subClassOf T(description1) . ...
```

```
classID rdfs:subClassOf T(descriptionn) .
```

Translating complete Class definition

Abstract Syntax

Class(classID complete *description*₁ ... *description*_n)

RDF graph

```
classID rdf:type owl:Class .
```

```
classID owl:intersectionOf T(SEQ description1 ...  
descriptionn) .
```

Translating complete Class definition

T(SEQ description1 ... descriptionn)

RDF graph

```
_:l1 rdf:type rdf:List . [opt]
```

```
_:l1 rdf:first T(item1) . _:l1 rdf:rest _:l2 .
```

...

```
_:ln rdf:type rdf:List . [opt]
```

```
_:ln rdf:first T(itemn) . _:ln rdf:rest rdf:nil .
```

Enumerated class

Abstract Syntax

EnumeratedClass(classID iID1 ... iIDn)

RDF graph

```
classID rdf:type owl:Class .  
classID owl:oneOf T(SEQ iID1 ... iIDn) .
```

Disjoint classes

Abstract Syntax

DisjointClasses(description1 ... descriptionn)

RDF graph

T(descriptionj) owl:disjointWith T(descriptioni) .

$1 \leq i < j \leq n$

Translating Union

Abstract Syntax

unionOf(description1 ... descriptionn)

RDF graph

```
_:x rdf:type owl:Class .  
_:x owl:unionOf T(SEQ description1 ...  
descriptionn) .
```

Translating Intersection

Abstract Syntax

intersectionOf(description1 ... descriptionn)

RDF graph

```
_:x rdf:type owl:Class .
```

```
_:x owl:intersectionOf T(SEQ description1 ...  
descriptionn) .
```

Translating Restrictions

Abstract Syntax

restriction(ID component1 ... componentn)

(With at least two components)

RDF graph

```
_:x rdf:type owl:Class .
```

```
_:x owl:intersectionOf
```

```
  T(SEQ(restriction(ID component1) ...
```

```
    restriction(ID componentn))) .
```

Translating Restrictions

Abstract Syntax

restriction(ID allValuesFrom(range))

RDF graph

```
_:x rdf:type owl:Restriction .  
_:x owl:onProperty T(ID) .  
_:x owl:allValuesFrom T(range) .
```

Translating Restrictions

Abstract Syntax

restriction(ID minCardinality(min))

RDF graph

```
_:x rdf:type owl:Restriction .
```

```
_:x owl:onProperty T(ID) .
```

```
_:x owl:minCardinality "min"^^xsd:nonNegativeInteger .
```

Translating Individuals

Abstract Syntax

Individual(iID

 type(type1) ... type(typen)

 value(pID1 v1) ... value(pIDk vk))

RDF graph

```
iID rdf:type T(type1) . ... iID rdf:type T(typen) .
```

```
iID T(pID1) T(v1) . ... iID T(pIDk) T(vk) .
```

RDF Rules: N3

- ▶ RDF Rules: extension of Turtle to **rules**
- ▶ `rdf:type` may be abbreviated to `a`
- ▶ Syntax:
$$\{ (triple\ pattern\ .)^* \} \Rightarrow \{ (triple\ pattern\ .)^* \} .$$
- ▶ Rule safety:
 - ▶ Variables on right-hand side of \Rightarrow (**head**) **must** occur on left-hand side **body**
- ▶ Variables implicitly universally quantified over rule
- ▶ \Rightarrow as standard implication in Logic Programming
- ▶ Rule with empty head is **integrity constraint**
- ▶ Rule with empty body is **fact**

RDF Rules: examples

```
{?A rdfs:subClassOf ?B. ?B rdfs:subClassOf ?A} =>  
  {?A owl:equivalentClass ?B}.
```

```
{?D owl:complementOf ?C.  
  ?D owl:equivalentClass owl:Nothing} =>  
  {?C owl:equivalentClass owl:Thing}.
```

```
{?A owl:differentFrom ?A} => {}.
```

Rule-based OWL reasoning

- ▶ Cannot **exactly** capture OWL DL semantics
- ▶ OWL DL semantics can be approximated to large extent, e.g., equality:
 - ▶ Equality not really in the (rule) language
 - ▶ Can be simulated with `owl:sameAs`
- ▶ Hard to characterized which part of Semantics is captured
- ▶ Can capture part of OWL Full semantics
- ▶ Rule-based RDF reasoning popular on Semantic Web (e.g. Jena, CWM, Euler, ...)

Basic Ideas of DLs

- ▶ Basic syntactic building blocks
 - ▶ Atomic concepts
 - ▶ Atomic roles
 - ▶ Individuals
- ▶ Limited constructs for building complex concepts, roles
- ▶ Implicit knowledge can be inferred automatically
 - ▶ Subsumption

Inference of implicit knowledge

Consider the TBox:

$Woman \equiv Person \sqcap Female$

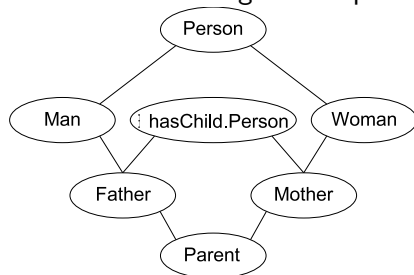
$Man \equiv Person \sqcap \neg Woman$

$Mother \equiv Woman \sqcap \exists hasChild.Person$

$Father \equiv Man \sqcap \exists hasChild.Person$

$Parent \equiv Mother \sqcup Father$

entails the following subsumption hierarchy:



Review of DL Basics

- ▶ Set-based term descriptions
- ▶ Intentional knowledge
 - ▶ A DL ontology is not a database!
- ▶ Main inference procedure: subsumption reasoning
 - ▶ If a concept D is more general than a concept C , it **subsumes** that concept:
 $C \sqsubseteq D$
- ▶ Efficient TBox reasoning
- ▶ ABox reasoning (query answering) not well developed

OWL constructs

OWL Construct	DL	Example
intersectionOf	$C_1 \sqcap \dots \sqcap C_n$	<i>Human</i> \sqcap <i>Male</i>
unionOf	$C_1 \sqcup \dots \sqcup C_n$	<i>Doctor</i> \sqcup <i>Lawyer</i>
complementOf	$\neg C$	\neg <i>Male</i>
oneOf	$\{o_1, \dots, o_n\}$	<i>{john, mary}</i>
allValuesFrom	$\forall P.C$	\forall <i>hasChild.Doctor</i>
someValuesFrom	$\exists P.C$	\exists <i>hasChild.Lawyer</i>
value	$\exists P.\{o\}$	\exists <i>citizenOf.USA</i>
minCardinality	$\geq nP.C$	≥ 2 <i>hasChild.Lawyer</i>
maxCardinality	$\leq nP.C$	≤ 1 <i>hasChild.Male</i>
cardinality	$= nP.C$	$= 1$ <i>hasParent.Female</i>

+ XML Schema datatypes: int, string, real, etc...

OWL axioms

OWL Axiom	DL	Example
SubClassOf	$C_1 \sqsubseteq C_2$	<i>Human</i> \sqsubseteq <i>Animal</i> \sqcap <i>Biped</i>
EquivalentClasses	$C_1 \equiv \dots \equiv C_n$	<i>Man</i> \equiv <i>Human</i> \sqcap <i>Male</i>
SubPropertyOf	$P_1 \sqsubseteq P_2$	<i>hasDaughter</i> \sqsubseteq <i>hasChild</i>
EquivalentProperties	$P_1 \equiv \dots \equiv P_n$	<i>cost</i> \equiv <i>price</i>
SameIndividual	$o_1 = \dots = o_n$	<i>President_Bush</i> = <i>G_W_Bush</i>
DisjointClasses	$C_i \sqsubseteq \neg C_j$	<i>Male</i> $\sqsubseteq \neg$ <i>Female</i>
DifferentIndividuals	$o_i \neq o_j$	<i>john</i> \neq <i>peter</i>
inverseOf	$P_1 \equiv P_2^-$	<i>hasChild</i> \equiv <i>hasParent</i> ⁻
Transitive	$P^+ \sqsubseteq P$	<i>ancestor</i> ⁺ \sqsubseteq <i>ancestor</i>
Symmetric	$P \equiv P^-$	<i>connectedTo</i> \equiv <i>connectedTo</i> ⁻

More examples

```
Class( firstYearCourse partial restriction (isTaughtBy allValuesFrom  
( Professor )))
```

```
Class(mathCourse partial restriction (isTaughtBy hasValue (949352)))
```

```
Class(academicStaffMember partial restriction (teaches someValuesFrom  
(undergraduateCourse)))
```

```
Class(course partial restriction (isTaughtBy minCardinality(1)))
```

```
Class(department partial restriction (hasMember minCardinality(10))  
restriction (hasMember maxCardinality(30)))
```

More examples

In DL syntax:

firstYearCourse $\sqsubseteq \forall isTaughtBy. Professor$

mathCourse $\sqsubseteq \exists isTaughtBy. \{949352\}$

academicStaffMember $\sqsubseteq \exists teaches. undergraduateCourse$

course $\sqsubseteq_{\geq 1} isTaughtBy$

department $\sqsubseteq_{\geq 10} hasMember \sqcap \leq 30 hasMember$

More examples

```
Class(course partial complementOf(staffMember))
```

```
Class(peopleAtUni complete unionOf(staffMember student))
```

```
Class(facultyInCS complete intersectionOf ( faculty  
restriction (belongsTo hasValue (CSDepartment))))
```

```
Class(adminStaff complete intersectionOf ( staffMember  
complementOf(unionOf(faculty techSupportStaff))))
```

More examples

In DL syntax:

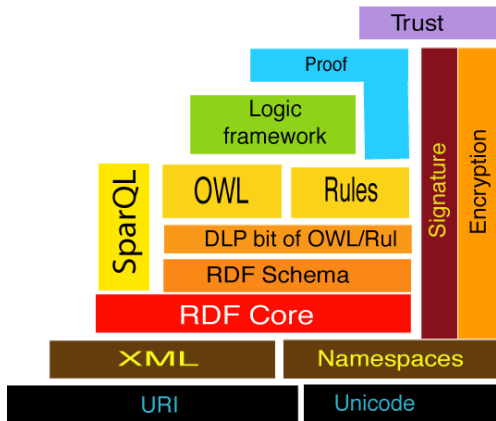
$course \sqsubseteq \neg staffMember$

$peopleAtUni \equiv staffMember \sqcup student$

$facultyInCS \equiv faculty \sqcap \exists belongsTo. \{CSDepartment\}$

$adminStaff \equiv staffMember \sqcap \neg (faculty \sqcup techSupportStaff)$

Semantic Web Languages



Why relate DL and LP?

Why not use DL or LP for everything?

- ▶ LP: Efficient algorithms and implementations for query answering
- ▶ DL: Efficient algorithms and implementations for subsumption reasoning
- ▶ Thus: it depends on the reasoning task which language to use
- ▶ Many existing implementations of rules systems (e.g., SQL1999 \approx Datalog with linear recursion)
- ▶ Web Ontology Language (OWL) based on DL
- ▶ Thus: in order to leverage existing rule implementations for the Semantic Web, we need to translate!

Recap: Logic Programming

- ▶ Any FOL term is a term in LP
- ▶ Any FOL atomic formula is an atomic formula in LP
- ▶ Any Horn formula is a rule in LP (quantification usually omitted)
 - ▶ $H \leftarrow B_1 \wedge \dots \wedge B_n$
- ▶ Logic programming is a syntactic subset of FOL
- ▶ **Note!** Negation-as-failure in LP is an **extension** of Horn rules
 - ▶ $\neg \neq \text{not}$

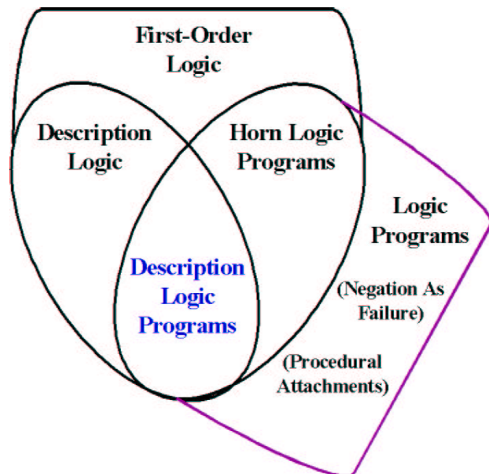
Entailment

- ▶ General First-Order entailment:
 - ▶ $\phi \models \psi$ iff for every interpretation \mathcal{I} : if $\mathcal{I} \models \phi$ then $\mathcal{I} \models \psi$
 - ▶ Thus, the set of models of ϕ $M(\phi)$ is a subset of $M(\psi)$:

$$M(\phi) \subseteq M(\psi)$$
 - ▶ e.g., $p(x) \wedge q(x) \models p(x)$
- ▶ Ground entailment:
 - ▶ $\phi \models \psi_{ground}$ iff for every interpretation \mathcal{I} : if $\mathcal{I} \models \phi$ then $\mathcal{I} \models \psi_{ground}$ and ψ_{ground} **does not** contain variables
 - ▶ e.g., $(p(x) \rightarrow q(x)) \wedge p(a) \models q(a)$
- ▶ Logic Programming only defines ground entailment
- ▶ Horn Logic (i.e., Horn subset of FOL) is equivalent to Logic Programming wrt. ground entailment
 - ▶ For any set of Horn formulas ϕ and a ground Horn formula ψ_{ground} :

$$\phi \models_{FOL} \psi_{ground} \text{ iff } \phi \models_{LP} \psi_{ground}$$
 - ▶ \models_{FOL} is classical First-Order entailment; \models_{LP} is LP entailment

Relation between DL and LP



Description Logic Programs

- ▶ “Intersection” of Description Logics and Logic Programming
- ▶ That part of Description Logics (OWL in particular) which can be translated to a Logic Program
- ▶ Horn Logic subset of *SHOIN*, **reduced** to a Logic Program: Description Logic Program: DLP
- ▶ General idea:
 1. Translate *SHOIN* axiom to First-Order Logic
 2. Rewrite to Horn Logic
 - ▶ If rewriting not possible: formula not in DLP
 3. Reduce to Logic Program

Recap: *SHOIN*

Concept descriptions

$C, D \longrightarrow A$		(atomic concept)
\top		(universal concept)
\perp		(bottom concept)
$C \sqcap D$		(intersection)
$C \sqcup D$		(disjunction)
$\neg C$		(negation)
$\forall R.C$		(value restriction)
$\exists R.C$		(existential quantification)
$\{o_1, \dots, o_n\}$		(enumeration)
$\exists R.\{o\}$		(hasValue)
$\geq nR$		(minimal cardinality)
$\leq nR$		(maximal cardinality)

Recap: *SHOIN*

Individual assertions

$$a \in C$$

$$\langle a, b \rangle \in R$$

Recap: *SHOIN*

Axioms

$C \sqsubseteq D$	(class subsumption)
$C \equiv D$	(equivalence)
$Q \sqsubseteq R$	(property subsumption)
$R \equiv Q^{-}$	(inverse roles)
$R \equiv R^{-}$	(symmetric roles)
$R^{+} \sqsubseteq R$	(transitive properties)

Mapping *SHOIN* to FOL

A (atomic concept)	$A(x)$
\top	\top
\perp	\perp
$C \sqcap D$	$tr(C) \wedge tr(D)$
$C \sqcup D$	$tr(C) \vee tr(C)$
$\neg C$	$\neg tr(C)$
$\forall R.C$	$\forall y : R(x, y) \rightarrow tr(C, y)$
$\exists R.C$	$\exists y : R(x, y) \wedge tr(C, y)$
$\{o_1, \dots, o_n\}$	$x = o_1 \vee \dots \vee x = o_n$
$\exists R.\{o\}$	$R(x, o)$
$\geq nR$	$\exists y_1, \dots, y_n : \bigwedge R(X, y_i) \wedge \bigwedge y_i \neq y_j$
$\leq nR$	$\forall y_1, \dots, y_{n+1} : \bigwedge R(X, y_i) \rightarrow \bigvee y_i = y_j$

Mapping *SHOIN* to FOL

$$\begin{array}{l|l}
 a \in A & A(a) \\
 \langle a, b \rangle \in R & R(a, b)
 \end{array}$$

$$C \sqsubseteq D \quad \left| \quad \forall x : tr(C, x) \rightarrow tr(D, x) \right.$$

$$C \equiv D \quad \left| \quad \forall x : tr(C, x) \leftrightarrow tr(D, x) \right.$$

$$Q \sqsubseteq R \quad \left| \quad \forall x, y : Q(x, y) \rightarrow R(x, y) \right.$$

$$R \equiv Q^- \quad \left| \quad \forall x, y : R(x, y) \leftrightarrow Q(y, x) \right.$$

$$R^+ \sqsubseteq R \quad \left| \quad \forall x, y, z : R(x, y) \wedge R(y, z) \rightarrow R(x, z) \right.$$

Identifying DLP (1)

- ▶ Next step: identify DLP-fragment of *SHOIN*
- ▶ Start with the axioms

- ▶ Easy case: properties

$$Q \sqsubseteq R \quad \left| \quad \forall x, y : Q(x, y) \rightarrow R(x, y)\right.$$

$$R \equiv Q^- \quad \left| \quad \forall x, y : R(x, y) \leftrightarrow Q(y, x)\right.$$

$$R^+ \sqsubseteq R \quad \left| \quad \forall x, y, z : R(x, y) \wedge R(y, z) \rightarrow R(x, z)\right.$$

All Horn Logic!

- ▶ Equivalence axioms: $C \equiv D$
 Reduce to: $C \sqsubseteq D, D \sqsubseteq C$
- ▶ Subsumption axioms: $C \sqsubseteq D \mapsto \forall x : tr(C, x) \rightarrow tr(D, x)$

$tr(C, x)$ is the **body** of the rule

$tr(D, x)$ is the **head** of the rule

Identifying DLP (2)

- ▶ $C \sqsubseteq D$
 - ▶ **Remember:** the **body** is a conjunction of literals; the **head** is a single literal
 - ▶ Thus: C and D look different
 - ▶ C is called the **left-hand side** (lhs)
 - ▶ D is called the **right-hand side** (rhs)
- ▶ We distinguish between:
 - ▶ Descriptions allowed on the left-hand side
 - ▶ Descriptions allowed on the right-hand side

Identifying DLP (3)

<i>SHOIN</i>	FOL	lhs	rhs
A (atomic concept)	$A(x)$	+	+
\top	\top	+/-	+
\perp	\perp	+	-
$C \sqcap D$	$tr(C) \wedge tr(D)$	+	+
$C \sqcup D$	$tr(C) \vee tr(C)$	+	-
$\neg C$	$\neg tr(C)$	-	-
$\forall R.C$	$\forall y : R(x, y) \rightarrow tr(C, y)$	-	+
$\exists R.C$	$\exists y : R(x, y) \wedge tr(C, y)$	+	-
$\{o_1, \dots, o_n\}$	$x = o_1 \vee \dots \vee x = o_n$	+	-
$\exists R.\{o\}$	$R(x, o)$	+	+
$\geq nR$	$\exists y_1, \dots, y_n : \bigwedge R(x, y_i) \wedge \bigwedge y_i \neq y_j$	+	-
$\leq nR$	$\forall y_1, \dots, y_{n+1} : \bigwedge R(x, y_i) \rightarrow \bigvee y_i = y_j$	-	-

Identifying DLP (4)

- ▶ Individual assertions:

$$\begin{array}{l|l} a \in A & A(a) \\ \langle a, b \rangle \in R & R(a, b) \end{array}$$

Trivially in DLP!

- ▶ Example: $\top \sqcap \exists P.A \sqcap \{o_1, o_2\} \sqcap B \sqsubseteq \forall P.B$

Step 1: rewrite to FOL:

$$\forall x : \top \wedge (\exists y : P(x, y) \wedge A(y)) \wedge (x = o_1 \vee x = o_2) \wedge B(x) \rightarrow (\forall y : P(x, y) \wedge B(y))$$

Step 2: rewrite to Horn Logic:

$$1: \forall x : \top \wedge (\exists y : P(x, y) \wedge A(y)) \wedge (x = o_1 \vee x = o_2) \wedge B(x) \rightarrow (\forall y : P(x, y) \wedge B(y)) \Leftrightarrow$$

Example (cont'd)

$$2: \forall x : \neg T \vee \neg(\exists y : P(x, y) \wedge A(y)) \vee \neg(x = o_1 \vee x = o_2) \vee \neg B(x) \vee (\forall y : P(x, y) \wedge B(y)) \Leftrightarrow$$

$$3: \forall x : \neg(\exists y : P(x, y) \wedge A(y)) \vee \neg(x = o_1 \vee x = o_2) \vee \neg B(x) \vee (\forall y : P(x, y) \wedge B(y)) \Leftrightarrow$$

$$4: \forall x : (\forall y : \neg(P(x, y) \wedge A(y))) \vee \neg(x = o_1 \vee x = o_2) \vee \neg B(x) \vee (\forall y : P(x, y) \wedge B(y)) \Leftrightarrow$$

$$5: \forall x, y : \neg P(x, y) \vee \neg A(y) \vee \neg(x = o_1 \vee x = o_2) \vee \neg B(x) \vee (\forall y : P(x, y) \wedge B(y)) \Leftrightarrow$$

Example (cont'd)

$$6: \forall x, y : \neg P(x, y) \vee \neg A(y) \vee (\neg x = o_1 \wedge \neg x = o_2) \vee \neg B(x) \vee (\forall y : P(x, y) \wedge B(y)) \Leftrightarrow$$

$$7: \forall x, y, z : \neg P(x, y) \vee \neg A(y) \vee (\neg x = o_1 \wedge \neg x = o_2) \vee \neg B(x) \vee (P(x, z) \wedge B(z)) \Leftrightarrow$$

$$8: \forall x, y, z : \neg P(x, y) \vee \neg A(y) \vee \neg x = o_1 \vee \neg B(x) \vee (P(x, z) \wedge B(z)) \vee \forall x, y, z : \neg P(x, y) \vee \neg A(y) \vee \neg x = o_2 \vee \neg B(x) \vee (P(x, z) \wedge B(z)) \Leftrightarrow$$

Example (cont'd)

$$9: \forall x, y, z : \neg P(x, y) \vee \neg A(y) \vee \neg x = o_1 \vee \neg B(x) \vee P(x, z)$$

$$\forall x, y, z : \neg P(x, y) \vee \neg A(y) \vee \neg x = o_1 \vee \neg B(x) \vee B(z)$$

$$\forall x, y, z : \neg P(x, y) \vee \neg A(y) \vee \neg x = o_2 \vee \neg B(x) \vee P(x, z)$$

$$\forall x, y, z : \neg P(x, y) \vee \neg A(y) \vee \neg x = o_2 \vee \neg B(x) \vee B(z)$$

Step 3: Reduce to Logic Program

$$P(x, z) \text{ :- } P(x, y), A(y), x=o_1, B(x).$$

$$B(z) \text{ :- } P(x, y), A(y), x=o_1, B(x).$$

$$P(x, z) \text{ :- } P(x, y), A(y), x=o_2, B(x).$$

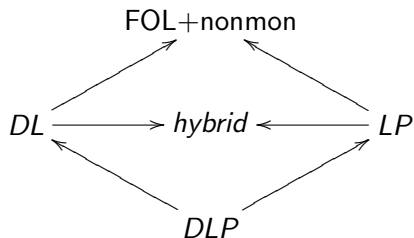
$$B(z) \text{ :- } P(x, y), A(y), x=o_2, B(x).$$

Semantic reduction: only entailment of ground atoms

Integration of DL and LP beyond DLP

- ▶ DLP has limited expressiveness
 - ▶ No disjunction
 - ▶ No existentials
 - ▶ No negation
 - ▶ No chaining variables over predicates
- ▶ DLP allows **extension** to DL or LP, no real **interoperation**

Outlook: Integration beyond DLP



- ▶ Extension of DLP
 - ▶ Interoperation only for inexpressive ontologies
- ▶ Unified language
 - ▶ Obviously undecidable
 - ▶ Little research has been done
- ▶ Hybrid integration
 - ▶ Full DL and LP
 - ▶ Interaction limited to retain decidability
 - ▶ Several existing approaches (e.g. [Eiter, 2004; Rosati, 2006])

Summary

OWL in RDF

Mapping OWL DL to RDF

Reasoning with OWL

RDF-based Rule Reasoning

DL-based Reasoning

OWL DL and Logic Programming

Description Logic Programs

Beyond DLP

Required reading

- ▶ OWL Guide: <http://www.w3.org/TR/owl-guide/>
- ▶ Ian Horrocks, Peter F. Patel-Schneider, and Frank van Harmelen. From SHIQ and RDF to OWL: The making of a web ontology language. **Journal of Web Semantics**, 1(1):7, 2003.

Further reading

- ▶ Grosz et al. Description logic programs: Combining logic programs with description logic. In **WWW-2003**.
- ▶ OWL Reference: <http://www.w3.org/TR/owl-ref/>
- ▶ OWL Abstract syntax and Semantics:
<http://www.w3.org/TR/owl-semantics/>
- ▶ T. Eiter, T. Lukasiewicz, R. Schindlauer, H. Tompits: Combining Answer Set Programming with Description Logics for the Semantic Web. In **KR 2004**.