# Semantic Web Modeling Languages

## Lecture 5: Rules

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Slides for remaining lectures at http://semantic-web-book.org/page/ESSLLI_2009

# Why Rules?

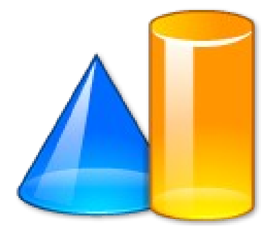
**OWL may not suffice for all applications**

- There are statements that cannot be expressed in OWL (cf. Lecture 4)
- Modeling constructs of OWL not always adequate or most desirable
- First-order logic in general may be insufficient (e.g. if non-monotonic negation is desired)

→ "Rules" as an alternative paradigm for knowledge modeling

# What is a Rule?

- Logical Rules (predicate logic implications)
  - “F → G” (equivalent to “¬F v G”)
  - Logical extension of a knowledge base (**static**)
  - **Open World**
  - Declarative (descriptive)
- Procedural Rules (e.g. production rules)
  - “If X then Y else Z”
  - Executable machine directive (**dynamic**)
  - **Operational** (meaning = effect on execution)
- Logic Programming (e.g. Prolog, F-Logic)
  - “`man(x) :- person(X), not woman(X)`”
  - Approximating logical semantics with procedural aspects, built-ins possible
  - Typically **Closed World**
  - “**semi-declarative**”
- Deduction rules of a calculus (e.g. rules for RDF semantics, lecture 1)
  - Rules not part of the knowledge base, “meta-rules”



# Which Rule Language?

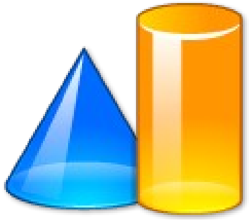
**Rule languages are hardly compatible with each other →** important to chose adequate rule language

Possible criteria:

- Clear specification of syntax and semantics?
- Support by software tools?
- Which expressive features are needed?
- Complexity of implementation? Performance?
- Compatibility with other formats, e.g. OWL?
- Declarative (describing) or operational (programming)?
- …

# Which Rule Language?

- **Logical Rules** (predicate logic implications)
  - Clearly defined, extensively researched, well understood
  - Very well compatible with OWL and RDF
  - Not decidable if unrestricted



- **Procedural Rules** (e.g. production rules)
  - Many independent approaches, vague definition
  - Used like programming languages, relation to RDF and OWL not clear
  - Efficient processing possible
- **Logic Programming** (e.g. Prolog, F-Logic)
  - Clearly defined, but many independent approaches
  - Partly compatible with OWL and RDF
  - Decidability/complexity depends very much on the chosen approach

→ In this lecture: predicate logic rules
(which are also the basis for logic programming)

# Predicate Logic as a Rule Language

- Rules as first-order logic implications (Horn clauses):

  $A1 \land A2 \land \ldots \land An \rightarrow H$ ("Body → Head")

  Example: "Man(x) ∧ happilyMarriedWith(x,y) → HappyHusband(x)"

- Constants, variables, function symbols can be used; but no negation
- Quantifiers are omitted: free variables considered universally quantified
- **Datalog:** rules without function symbols
  - Originally developed for deductive databases
  - Knowledge bases ("datalog programs") are sets of function-free Horn clauses
  - Decidable
  - efficiently implementable for large datasets (overall complexity ExpTime, i.e. "Draughts" or "Chess")

# Semantics of Datalog?

- Semantics follows from first-order logic:
  - Generally well-known
  - Compatible with other first-order fragments, e.g. description logics (→ OWL)

Note: to maintain this relationship, we will prefer FOL syntax "hasCat(*x*,*y*)" over Turtle style "*x* hasCat *y*" or "triple(*x*,hasCat,*y*)."

# SWRL

How can datalog and OWL be combined?

**SWRL – Semantic Web Rule Language** [swirl]

- Proposal for a rule extension for OWL (W3C member submission)
- Idea: datalog rules referring to an OWL ontology
  → Symbols in rules can be OWL identifiers or new symbols
- Various further features and syntactic forms (not relevant here)

# Semantics of SWRL

**Combined semantics OWL DL + datalog?**
→ use first-order mapping of OWL (lecture 2)

In effect:

- OWL individuals are datalog constants
- OWL classes are unary datalog predicates
- OWL properties are binary datalog predicates

→ A first-order interpretation can at the same time be a model for an OWL ontology and a datalog program
→ Entailment over OWL+datalog (SWRL) well-defined

# Example: SWRL knowledge base

For readability, we abbreviate URIs strongly here; the datalog syntax does not follow a formal specification (SWRL XML is too verbose here)

```
(1)   Vegetarian(x) ∧ Fishproduct(y)  → dislikes(x,y)
(2)     ordered(x,y) ∧ dislikes(x,y)  → Unhappy(x)
(3)                      ordered(x,y)  → Dish(y)
(4) dislikes(x,z) ∧ Dish(y) ∧ contains(y,z) → dislikes(x,y)
(5)                                    → Vegetarian(markus)
(6)           Happy(x) ∧ Unhappy(x)   →

(7) markus rdf:type [
       rdf:type            owl:Restriction;
       owl:onProperty      ordered;
       owl:someValuesFrom  ThaiCurry          ]
(8) ThaiCurry rdfs:subClassOf [
       rdf:type            owl:Restriction;
       owl:onProperty      contains;
       owl:someValuesFrom  Fishproduct        ]
```

# Example: SWRL knowledge base

OWL DL can be translated to first-order logic:

```
(1)  Vegetarian(x) ∧ Fishproduct(y)  → dislikes(x,y)
(2)     ordered(x,y) ∧ dislikes(x,y)  → Unhappy(x)
(3)                       ordered(x,y)  → Dish(y)
(4) dislikes(x,z) ∧ Dish(y) ∧ contains(y,z) → dislikes(x,y)
(5)                                      → Vegetarian(markus)
(6)            Happy(x) ∧ Unhappy(x)  →

(7) ∃y.ordered(markus,y) ∧ ThaiCurry(y)
(8) ∀x.ThaiCurry(x) → (∃y.contains(x,y) ∧ FishProduct(y))
```

→ Semantics completely defined

→ Expected conclusion: **Unhappy(markus)**

Note: empty rule heads correspond to "false" (rule body must never be true)
empty rule bodies correspond to "true" (rule head must always be true)

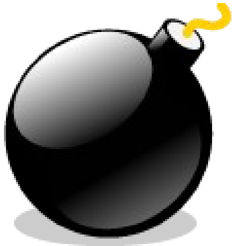
# How Hard is SWRL?

- Deduction for OWL DL is NExpTime-complete
- Deduction for OWL 2 DL is N2ExpTime-complete
- Deduction in datalog is ExpTime-complete

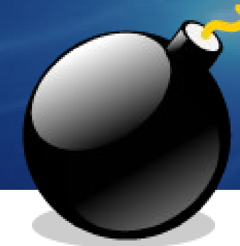
→ How hard is deduction for SWRL?

**Deduction for SWRL is undecidable**

(for OWL and thus for OWL 2, even for OWL EL)



# Undecidability of SWRL



**SWRL is undecidable:**
There is no algorithm that can draw *all* logical conclusions from *all* SWRL knowledge bases, even with unlimited time and resources.

**Practically possible:**

- Algorithms that draw *all* conclusions for *some* SWRL knowledge bases
- Algorithms that draw *some* conclusions from *all* SWRL knowledge bases

→ Both trivial if "some" refers to very few things

# Decidable Fragments of SWRL

Which classes of SWRL knowledge bases allow for complete inference algorithms?

- All SWRL knowledge bases consisting only of OWL (2) axioms
- All SWRL knowledge bases only consisting of datalog rules
- Every fixed finite class of SWRL knowledge bases

→ Which more interesting decidable fragments exist?

- **Description Logic Rules**
- **DL-safe Rules**

# Description Logic Rules

**Observation:**
Some SWRL-rules can already be expressed in OWL 2.

- Identifying all such Description Logic Rules leads to a decidable fragment
- Goal: Exploit "hidden" expressivity of OWL 2
- Implementation directly by OWL 2 tools

# Simple Rules in OWL 2: Examples

- Simple OWL 2 axioms correspond to rules:

```
Class1       rdfs:subClassOf       Class2 .
Property1    rdfs:subPropertyOf    Property2 .
```

correspond to

```
     Class1(x)    →   Class2(x)
Property1(x,y)    →   Property2(x,y)  .
```

# Simple Rules in OWL 2: Examples

- Some classes can be decomposed in rules:

```
[ owl:intersectionOf ( Happy  Unhappy ) ]
                       rdfs:subClassOf      owl:Nothing .

[ rdf:type            owl:Restriction;
  owl:onProperty      livesIn;
  owl:someValuesFrom [ rdf:type  owl:Restriction;
                       owl:onProperty  locatedIn;
                       owl:someValuesFrom EUCountry ]
                     ]
] rdfs:subClassOf  EUCitizen .
```

correspond to

```
    Happy(x) ∧ Unhappy(x)  →
livesIn(x,y) ∧ locatedIn(y,z) ∧ EUCountry(z)  →  EUCitizen(x)
```

# Simple Rules in OWL 2: Examples

- Property chains provide further rule-like axioms:

```
hasUncle owl:PropertyChainAxiom ( hasParent  hasBrother ).
```

correspond to

```
hasParent(x,y) ∧ hasBrother(y,z) → hasUncle(x,z)
```

→ In all examples, mapping can also be inverted (expressing rules in OWL 2)

# More Rules (I)

What about the following?

```
dislikes(x,z) ∧ Dish(y) ∧ contains(y,z) → dislikes(x,y)
```

- Rule head with two variables → not representable by subclass axiom
- Rule body contains class expression → not representable by subproperty axiom

**Yet, this rule can be encoded using OWL 2!**

# More Rules (2)

Simpler example:

```
Man(x) ∧ hasChild(x,y) → fatherOf(x,y)
```

Idea: replace **Man(x)** by a property expression to encode rule as property chain

- Self can be used to transform classes to properties:
  - Auxiliary property **PMan**
  - Auxiliary axiom:

```
Man owl:equivalentClass [ rdf:type owl:Restriction;
  owl:onProperty PMan;  owl:hasSelf "true"^^xsd:boolean ].
```

  - "Men are exactly those things that have an **PMan** relation to themselves."

We can now encode the rule as follows:

```
fatherOf    owl:propertyChainAxiom    ( PMan   hasChild ) .
```

# More Rules (3)

```
dislikes(x,z) ∧ Dish(y) ∧ contains(y,z) → dislikes(x,y)
```

becomes

```
Dish owl:equivalentClass [ rdf:type owl:Restriction;
  owl:onProperty PDish; owl:hasSelf "true"^^xsd:boolean ].

dislikes  owl:propertyChainAxiom
            ( dislikes  [owl:inverseOf contains]  PDish ).
```

# More Rules (4)

Not so simple:

```
Vegetarian(x) ∧ Fishproduct(y) → dislikes(x,y)
```

Idea: use **`owl:topObjectProperty`** for linking unconnected rule body parts

- Self can be used to transform classes to properties:
  - Auxiliary properties **`PVegetarian`** and **`PFishproduct`**
  - Axioms:

```
Vegetarian owl:equivalentClass [
  rdf:type owl:Restriction;  owl:onProperty PVegetarian;
  owl:hasSelf "true"^^xsd:boolean ].
Fishproduct owl:equivalentClass [
  rdf:type owl:Restriction;  owl:onProperty PFishproduct;
  owl:hasSelf "true"^^xsd:boolean ].
dislikes  owl:propertyChainAxiom
         ( PVegetarian  owl:topObjectProperty  PFishproduct ).
```

# Limits of Description Logic Rules

**Not all rules can be encoded like this!** Example:

```
ordered(x,y) ∧ dislikes(x,y) → Unhappy(x)
```

Overview of possible transformations:

- Inverting properties
- “Rolling-up” side branches, e.g.

```
locatedIn(x,y) ∧ EUCountry(y)        becomes

[ rdf:type             owl:Restriction;
  owl:onProperty       locatedIn;
  owl:someValuesFrom   EUCountry         ]
```

- Replacing concepts by properties (using `hasSelf`)
- Turn property conjunctions into chains

# Defining Description Logic Rules

- Preparation: **Normalise rule**
  - For each occurrence (!) of an individual name ***n*** in the rule:
    Use a fresh variable **x**, add `[owl:oneOf n](x)` to rule body, and replace the occurrence of ***n*** by **x**.
  - Replace every atom `P(x,x)` by
    `[rdf:type owl:Restriction; owl:onProperty P; owl:hasSelf "true"^^xsd:boolean](x).`
- **Dependency graph of a rule:** undirected graph where
  - Nodes = variables of a rule
  - Edges = property atoms of a rule (direction is ignored)
- **A SWRL rule is a Description Logic Rule if:**
  - All rule atoms use OWL 2 class and property names only
  - The normalised rule's dependency graph has no cycles

# Example

| | | | |
|---|---|---|---|
| (1) | Vegetarian(x) ∧ Fishproduct(y) | → dislikes(x,y) | ✓ |
| (2) | ordered(x,y) ∧ dislikes(x,y) | → Unhappy(x) | ✗ |
| (3) | ordered(x,y) | → Dish(y) | ✓ |
| (4) | dislikes(x,z) ∧ Dish(y) ∧ contains(y,z) | → dislikes(x,y) | ✓ |
| (5) | | → Vegetarian(markus) | ✓ |
| (6) | Happy(x) ∧ Unhappy(x) | → | ✓ |

Note: Restrictions like regularity and simplicity must still be satisfied after the translations.

# Transforming DL Rules to OWL 2

**Input:** A Description Logic Rule

(1) Normalise the rule.

(2) For every variable `z` in the head: if `z` is not in body, add `owl:Thing(z)` to body.

(3) For every pair of variables `x` and `y`:
If `x` is not reachable from `y` in the dependency graph, insert
`owl:topObjectProperty(x,y)` into the rule

(4) The rule head must have a form `D(z)` or `S(z,z')`.
For every atom `R(x,y)` in the rule body:
If the path from `z` to `y` is shorter than the path from `z` to `x` in the dependency graph, then replace `R(x,y)` with `[owl:inverseOf R](y,x)`.

*(5) While* the rule body contains an atom `R(x,y)` such that y does not occur in any other binary predicate of the rule *do*:

- If the body contains n unary atoms `C1(y)`, …, `Cn(y)` then let `E` denote the expression `[owl:intersectionOf (C1 … Cn)]` and remove `C1(y)`, …, `Cn(y)` from the body. Otherwise define `E` to be `owl:Thing`.
- Replace `R(x,y)` by: `[rdf:type owl:Restriction; owl:onProperty R; owl:someValuesFrom E](x)`

# Transforming DL Rules to OWL 2

The rule can now be expressed in OWL 2:

- If the rule head is unary, then the rule has the form `C1(x) ∧ … ∧ Cn(x) → D(x)` then replace it by

```
[owl:intersectionOf (C1, …, Cn)] rdfs:subClassOf D
```

- If the rule head is binary
  - For every unary atom `C(z)` in the rule body:
    Create a new axiom

```
C owl:equivalentClass [ rdf:type owl:Restriction;
  owl:onProperty R; owl:hasSelf "true"^^xsd:boolean ].
```

    and replace `C(z)` by `R(z,z)`, where `R` is a fresh property.
  - Rule now has the form `R1(x,x2) ∧…∧ Rn(xn,y) → S(x,y)`. Replace it by:

```
S owl:propertyChainAxiom ( R1 … Rn ).
```

# Notes on the Transformation

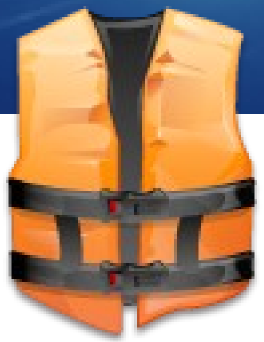
- Replacing a SWRL rule in a SWRL knowledge base by the resulting set of OWL 2 axioms does not affect satisfiability (introduced auxiliary symbols do not occur elsewhere, of course)
- The given algorithm is not optimised: it may produce overly complex axioms in some cases

# DL-safe Rules

**Observation:** Datalog is decidable since rules can be applied in only finitely many ways: variables represent only constants.

- Variables in SWRL might represent arbitrarily many infered individuals
- Goal: Make rules "safe" by restricting possible variable assignments
- **DL-safe rules** as another decidable fragment of SWRL

# DL-safe Rules: Definition



Rules now may also include non-OWL predicates:

- A **datalog atom** is an atom with a predicate symbol that does not occur as a class or property in any OWL axiom.

A SWRL rule is **DL-safe** if:

- Every variable in the rule head occurs in a datalog atom in the body.

→ Only constant symbols relevant when considering variable assignments in datalog atoms.

# Enforcing DL-Safety

- Example:

```
ordered(x,y) ∧ dislikes(x,y) → Unhappy(x)
```

→ not DL-safe if ***ordered*** or ***dislikes*** occur in OWL axioms

- Enforcing DL-safety by restricting rules to **named** individuals:

```
ordered(x,y) ∧ dislikes(x,y) ∧ O(x) ∧ O(y) → Unhappy(x)
```

where a fact → `O(a)` is added for all individuals ***a***.

→ Rule only applicable to **named** OWL individuals

# DL-Safe Rules in Practice

- OWL 2 with DL-safe rules is decidable
- Naïve implementation: each rule expressible by finitely many DL rules where all variables are replaced by individual symbols in all possible ways (very inefficient)
- No increase in worst-case complexity

Implementations:

- Basic support in some reasoners (KAON2, Pellet)
- Implementation in tableau-based tools complicated

# A Combined Example

OWL 2 + Description Logic Rules + DL-safe rules still decidable:

```
(1)   Vegetarian(x) ∧ Fishproduct(y)   → dislikes(x,y)
(2)ordered(x,y) ∧ dislikes(x,y) ∧ O(x) ∧ O(y)  → Unhappy(x)
(3)                        ordered(x,y)  → Dish(y)
(4) dislikes(x,z) ∧ Dish(y) ∧ contains(y,z)   → dislikes(x,y)
(5)                                      → Vegetarian(markus)
(6)            Happy(x) ∧ Unhappy(x)     →
(7) markus rdf:type [
       rdf:type            owl:Restriction;
       owl:onProperty      ordered;
       owl:someValuesFrom ThaiCurry          ]
(8) ThaiCurry rdfs:subClassOf [
       rdf:type            owl:Restriction;
       owl:onProperty      contains;
       owl:someValuesFrom Fishproduct        ]
(9) → O(markus)
```

→ We cannot conclude **Unhappy(markus)**

# A Combined Example

Explicitly use named individual:

```
(1)  Vegetarian(x) ∧ Fishproduct(y)   → dislikes(x,y)
(2)ordered(x,y) ∧ dislikes(x,y) ∧ O(x) ∧ O(y) → Unhappy(x)
(3)                     ordered(x,y)  → Dish(y)
(4) dislikes(x,z) ∧ Dish(y) ∧ contains(y,z)  → dislikes(x,y)
(5)                                   → Vegetarian(markus)
(6)           Happy(x) ∧ Unhappy(x)   →
(7) markus        ordered   redThaiCurry .
    RedThaiCurry  rdf:type  ThaiCurry .
(8) ThaiCurry rdfs:subClassOf [
       rdf:type           owl:Restriction;
       owl:onProperty     contains;
       owl:someValuesFrom Fishproduct        ]
(9) → O(markus)        → O(redThaiCurry)
```

→ Now we can conclude **Unhappy(markus)**

# Summary: Rules

- SWRL (“OWL+ datalog”) is undecidable
- Description Logic Rules:
  - SWRL fragment expressible in OWL 2
  - Supported indirectly by OWL 2 reasoners
  - Definition and translation based on dependency graph
- DL-safe rules:
  - SWRL fragment where variables can only assume concrete values
  - Support by some OWL reasoners
  - DL-safety can be enforced (also done implicitly in some tools)
- Combination OWL 2 + DL Rules + DL-safe rules possible

# Rules for the Semantic Web?

- Standards and best-practices for rules still missing
- SWRL syntax most widely used in applications
- W3C RIF (Rule Interchange Format) Working Group
  - Standard for various rule languages, also SWRL-like rules
  - Various new features, e.g. syntax from Frame Logic
  - Official specification expected by end 2009
- Many studies on interfacing Logic Programming and OWL
- OWL 2 RL: a profile that can be translated to datalog rules
  (note: inverse direction of Description Logic Rules)
  → enables some interoperability OWL 2 ↔ RIF
- Operational "inference rules" or "production rules" supported by some RDF-stores (e.g. Jena)

# Outlook: Semantic Web Research

This lecture covered basic technologies – many challenges remain:

- **How to create ontologies?**
  Engineering aspects, tools, automatic annotation, ontology learning, NLP, evaluation, …
- **How to deploy ontologies?**
  Applications in specific fields, e.g. e-science, life sciences, engineering, e-government, Web Services, …
- **How to process large amounts of semantic information?**
  Scalable reasoning, search and querying, distribution, algorithms, …
- **How to gather and combine semantic data?**
  Information integration, ontology mapping, crawling, …
- **How to explain all this to normal people?**
  User interfaces, deployment processes, tool integration, …
- **… contributions are welcome!**

# The Final Matrix Quote

*"I didn't come here to tell you how this is going to end. I came here to tell you how it's going to begin…*

*Where we go from there is a choice I leave to you.*

# Further Reading

- P. Hitzler, S. Rudolph, M. Krötzsch: **Foundations of Semantic Web Technologies.** CRC Press, 2009. (Chapter 6 closely related to this lecture; this also contains more references on types of rules not discussed here)
- I. Horrocks, P.F. Patel-Schneider, H. Boley, S. Tabet, B. Grosof, M. Dean. **SWRL: A Semantic Web Rule Language.** W3C Member Submission, 21 May 2004. Available at http://www.w3.org/Submission/SWRL/. (description of SWRL)
- **RIF working group homepage** (containing current status and pointers to documents): http://www.w3.org/2005/rules/wiki/RIF_Working_Group.
- S. Abiteboul, R. Hull, V. Vianu. **Foundations of Databases.** Addison Wesley, 1994. (the "Alice book" is an excellent resource on datalog)

Selected research articles:

- M. Krötzsch, S. Rudolph, P. Hitzler. **Description Logic Rules.** In Proc. 18th European Conf. on Artificial Intelligence (ECAI 2008), IOS Press, 2008. (original reference on Description Logic Rules)
- M. Krötzsch, S. Rudolph, P. Hitzler. **ELP: Tractable rules for OWL 2.** In Proc. 7th Int. Semantic Web Conf. (ISWC 2008), Springer, 2008. (extension of DL Rules to light-weight languages related to OWL EL and OWL RL)
- B. Motik, U. Sattler, R. Studer. **Query answering for OWL DL with rules.** Journal of Web Semantics, 3(1):41?60, 2005. (original reference on DL-safe rules)
- B.N. Grosof, I. Horrocks, R. Volz, S. Decker. **Description logic programs: combining logic programs with description logic.** In Proc. 12th Int. World Wide Web Conference (WWW-03), ACM, 2003. (original paper introducing DLP, a description logic that can be translated to datalog; closely related to OWL 2 RL)