OWL 2 and SWRL Tutorial

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This page explains the Web Ontology Language OWL 2 to us who are visually oriented. It also shows how to use an OWL ontology with SWRL rules from Java code by calling a reasoner.
Please note that this page describes OWL version 2, which can be processed only by tools designed for that version, like Protege 4, OWL API 3 or Pellet 2. Tools designed for the older OWL version 1, like Protege 3, will not work with the examples.

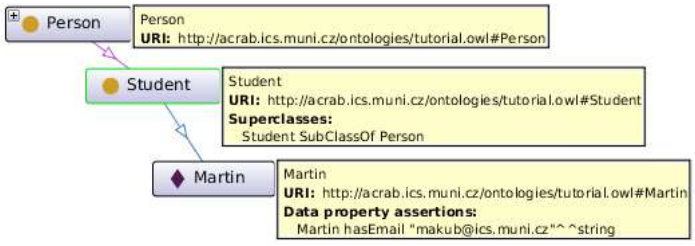
Content

OWL Ontology

OWL **ontology** is a set of **axioms**, which provide explicit logical assertions about three types of things - **classes**, **individuals** and **properties**. By using a piece of software called a **reasoner** we can infer other facts which are implicitly contained in the ontology, for example if an individual Martin is in class Student, and the class Student is a subclass of the class Person, a reasoner will infer that Martin is a Person.

There are two types of properties in OWL ontologies. **Data properties** are binary relations that link an individual to a piece of typed data, like to an xsd:dateTime or xsd:string literal. **Object properties** are binary relations that link an individual to an individual.

There are many ways how an OWL ontology can be *written*, however the important thing is the ontology *meaning*, which can be shown in a picture. I use here the Ontograf images produced by Protege OWL editor. For example, here is a small ontology with two classes and an individual, which has one data property:



The same axiom can be written in several ways. The most common is the XML/RDF format, the OWL 2 specification uses the *functional syntax* format, the Protege authors developed a shorter Manchester format, and the most concise format is Turtle. I will use the functional syntax format in this tutorial, and in some cases I will show also the Manchester syntax when it is more understandable.

Axiom types

There are many types of axioms that can be expressed in OWL 2. Let's list them here.

Declarations

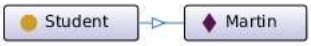
Class declaration defines a class. A class may contain individuals.


```
Declaration( Class( :Person ) )
```

Individual declaration defines a named individual.

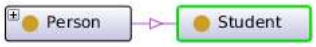

```
Declaration( NamedIndividual( :Martin ) )
```

Class assertion state that an individual belongs to a class:




```
ClassAssertion( :Student :Martin )
```

Subclass assertion declares that all individuals that belong to a class belong also to another class.




```
SubClassOf( :Student :Person )
```

Property declaration defines either a data property to link an individual to data, or object property to link to an individual:

```
Declaration( DataProperty( :hasEmail ) )

Declaration( ObjectProperty( :hasSpouse ) )
```

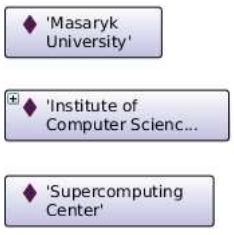
Property assertion states the relation of an individual to either data or individual:


```
DataPropertyAssertion( :hasEmail :Martin "makub@ics.muni.cz"^^xsd:string )

ObjectPropertyAssertion( :hasSpouse :Martin :Lenka )
```

Negative property assertion states that the relation of an individual to either data or individual **does not exist**. OWL uses Open World Assumption, so if an individual is not linked by some property with some value, it may be caused by two reasons - either it really does not have the property with the value, or it is **unknown** because the information missing from the ontology. A negative property assertion states that the individual cannot possibly have that property value.

```
NegativeObjectPropertyAssertion( :hasSpouse :Martin :Peter)
NegativeDataPropertyAssertion( :hasEmail :Martin "president@whitehouse.gov")
```

Annotation assertion enables to annotate anything with some details, for example we may use ICS as the name of an individual because it is an abbreviation, and use annotation to label the abbreviation with the full meaning "Institute of Computer Science". The images generated by Protege then show the label instead of the name.




```
Declaration( NamedIndividual( :MU ))
AnnotationAssertion( rdfs:label :MU "Masaryk University" )

Declaration( NamedIndividual( :ICS ) )
AnnotationAssertion( rdfs:label :ICS "Institute of Computer Science" )

Declaration( NamedIndividual(:SC) )
AnnotationAssertion( rdfs:label :SC "Supercomputing Center" )
```

Property axioms

We can define many things about properties (see OWL 2 Syntax - Object Property Axioms and OWL2 Direct Semantic - Object Property Expression Axioms for details), that a property is **transitive**, **symmetric**, **asymmetric**, **reflexive**, **irreflexive**, **functional** (can have only one value), **inverse-functional** (its inverse is functional), **inverse**

to some other property, **subproperty** of some other property, **equivalent** to some other property, or **disjoint** with some other property (two individuals cannot be linked by both properties in the same time).

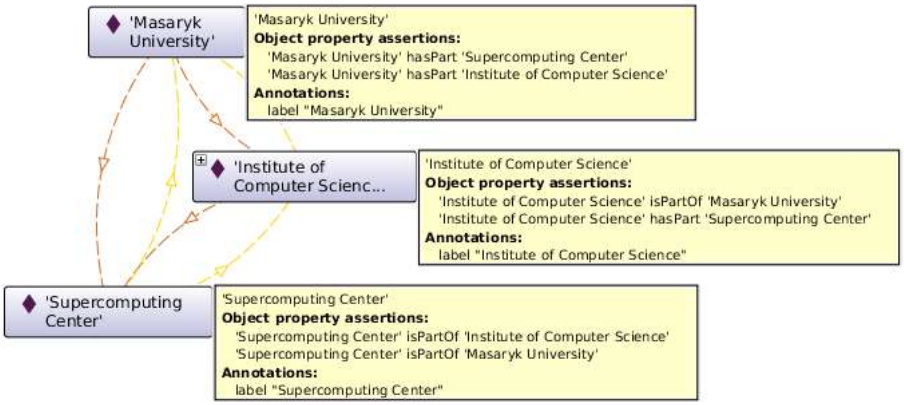
In a simple example, we can define that the property *hasSpouse* is **symmetric**, **functional** and **irreflexive**:


```
SymmetricObjectProperty( :hasSpouse )
FunctionalObjectProperty( :hasSpouse )
IrreflexiveObjectProperty( :hasSpouse )
```

In a more elaborate example, in the following image, a new **transitive** property *isPartOf* is defined, which connects the organizational parts of Masaryk University. Then the property *hasPart* is defined as an **inverse** property to *isPartOf*.


```
Declaration( ObjectProperty( :isPartOf ))
TransitiveObjectProperty( :isPartOf )

ObjectPropertyAssertion( :isPartOf :SC :ICS )
ObjectPropertyAssertion( :isPartOf :ICS :MU )

Declaration( ObjectProperty(:hasPart) )
InverseObjectProperties( :hasPart :isPartOf )
```

Now we can use a **reasoner** to infer the other properties. Because the isPartOf is transitive, SCB isPartOf MU, and because hasPart is inverse to isPartOf, we get the complete inferred relations:



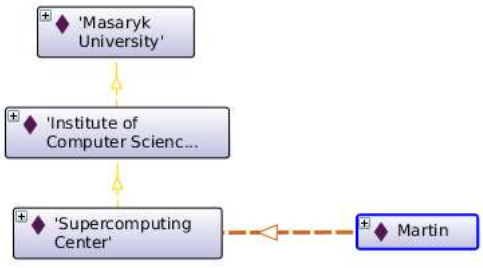

```
ObjectPropertyAssertion( :isPartOf :SC :MU )
ObjectPropertyAssertion( :hasPart :MU :SC )
ObjectPropertyAssertion( :hasPart :MU :ICS )
ObjectPropertyAssertion( :hasPart :ICS :SC )
```

It shows the power of reasoning - we do not have to declare all relations, just the needed minimum, and the rest can be inferred.

Property chains

The version 2 of OWL introduced important new feature - **chained properties**. They allow to define some relationships among three individuals, the most prominent example is the property *uncle* which may be defined as chain of *parent* and *brother* properties.

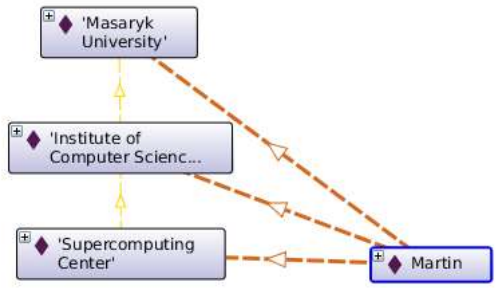
A property may be chained even with itself. For example, we may define property *isEmployedAt*, which is a chain of itself and the transitive property *isPartOf*, meaning that if a person is imployed at some organizational unit, the person is also employed at the bigger organizational units.




```
Declaration( ObjectProperty( :isEmployedAt ) )

ObjectPropertyAssertion( :isEmployedAt :Martin :SC )

SubObjectPropertyOf( ObjectPropertyChain( :isEmployedAt :isPartOf ) :isEmployedAt)
```

Again, using a reasoner we may infer the complete relations:

```
ObjectPropertyAssertion( :isEmployedAt :Martin :ICS )
ObjectPropertyAssertion( :isEmployedAt :Martin :MU )
```



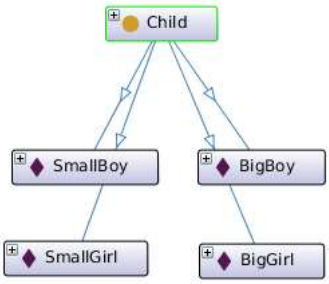
Class expressions

Classes may be defined using **class expressions**. (For details, see OWL 2 Syntax - Class expressions and OWL 2 Direct Semantics - Class Expression Axioms.) A common class definition is an assertion that a named class is **equivalent** to some (unnamed/anonymous) class defined by an expression. Classes can also be defined as **disjoined** with other class which means that they do not share any individuals.

Set operations: enumeration, union, intersection, complement

OWL 2 provides set operations in their usual mathematical meaning.

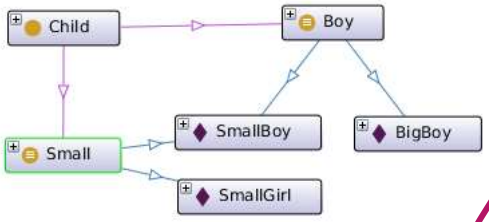
Let's show the set operations on an example. We can define a new class *Child* which contains four new individuals named *SmallBoy, BigBoy, SmallGirl, BigGirl*. These individuals must be declared as different from each other, otherwise an OWL reasoner expects that they may be the same:




```
Declaration( Class( :Child ) )
Declaration( NamedIndividual( :BigBoy ) )
Declaration( NamedIndividual( :BigGirl ) )
Declaration( NamedIndividual( :SmallBoy ) )
Declaration( NamedIndividual( :SmallGirl ) )
ClassAssertion( :Child :BigBoy )
ClassAssertion( :Child :BigGirl )
ClassAssertion( :Child :SmallBoy )
ClassAssertion( :Child :SmallGirl )
DifferentIndividuals( :BigBoy :BigGirl :SmallBoy :SmallGirl )
```

Enumeration

Let's define two base classes by enumerating their members, the *Boy* class containing boys and the *Small* class containing the small children. I.e. the individual SmallBoy is both in Boy and in Small classes. Here the functional syntax is not as nice as the Manchester syntax used in the Protege OWL editor, so both syntaxes are shown:



functional syntax:

```
SubClassOf(:Boy :Child)
SubClassOf(:Small :Child)
EquivalentClasses(:Boy ObjectOneOf(:SmallBoy :BigBoy))
EquivalentClasses(:Small ObjectOneOf(:SmallBoy :SmallGirl))
```

Manchester syntax:

```
Class: Boy
    EquivalentTo:
        {BigBoy , SmallBoy}
    SubClassOf:
        Child

Class: Small
    EquivalentTo:
        {SmallBoy , SmallGirl}
    SubClassOf:
        Child
```

Complement and intersection

Now we can define a new class *Girl* as a class that is the **intersection** of the class *Child* with an unnamed class that is the **complement** of the class *Boy*. This is a bit complicated description, the same is more intuitive in the Protege/Manchester format, where *Girl* class is equivalent to **Child and not Boy**, i.e. a girl is a child that is not a boy.

With such definition, a reasoner will find that the Girl class contains the individuals SmallGirl and BigGirl.

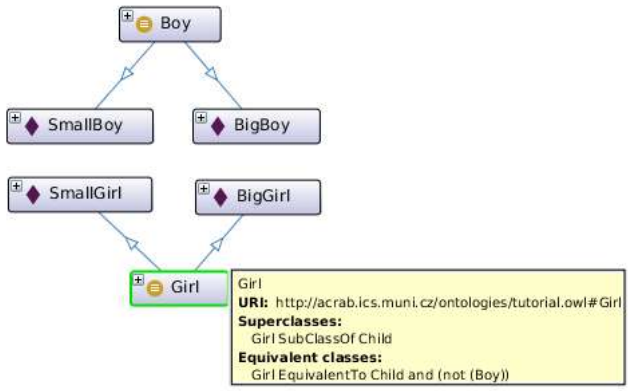
functional syntax:

```
Declaration( Class( :Girl ) )
SubClassOf( :Girl :Child )
EquivalentClasses( :Girl ObjectIntersectionOf( ObjectComplementOf( :Boy ) :Child )
```

Protege syntax:

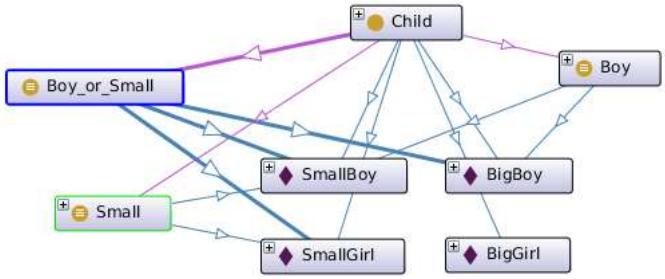
```
Class: Girl
    SubClassOf:
        Child
    EquivalentTo:
```

```
Child and (not (Boy))
```



Union

We can define a new class *Boy_or_small* as the **union** of the classes *Small* and *Boy*. Again, the description is more intuitive in the Protege syntax as **Boy or Small**. A reasoner will find that the class contains the individuals *SmallBoy, SmallGirl, BigBoy*:



functional syntax:

```
Declaration( Class( :Boy_or_Small ) )
EquivalentClasses( :Boy_or_Small ObjectUnionOf( :Small :Boy ) )
```

Protege syntax:

```
Class: Boy_or_Small
    EquivalentTo:
        Boy
         or Small
```

Existential Quantification

A class expression can say that the class contains only individuals that are connected by a given property with individuals from a given class. Let's show it on an example. We may define a new class OrgUnit which contains the three individuals MU, ICS, SC.

```
Declaration( Class( :OrgUnit ))
ClassAssertion( :OrgUnit :ICS )
ClassAssertion( :OrgUnit :MU )
ClassAssertion( :OrgUnit :SC )
```

Then we may define a new class *Employee* as a subclass of *Person*, which is **equivalent** to an anonymous class of individuals that are linked by property *isEmployedAt* to individuals from the class *OrgUnit*. The meaning is that employees are the persons that are employed somewhere:

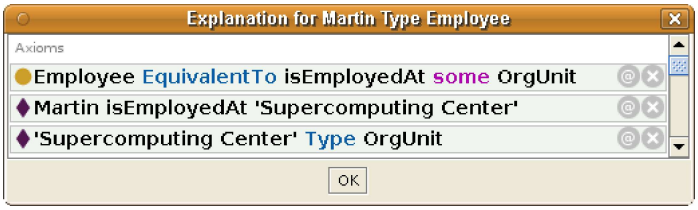
functional syntax:

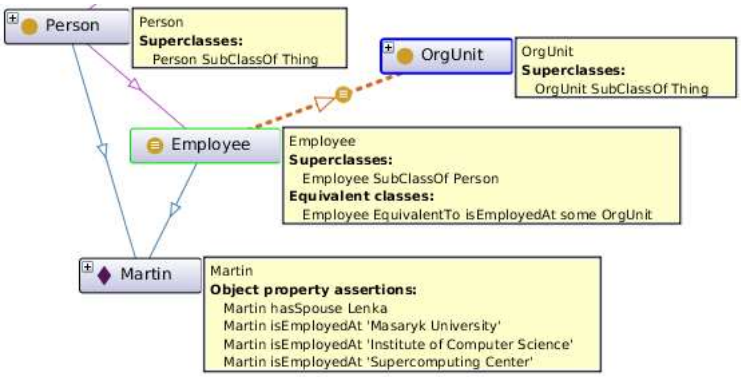
```
Declaration( Class( :Employee) )
SubClassOf( :Employee :Person )
EquivalentClasses( :Employee ObjectSomeValuesFrom( :isEmployedAt :OrgUnit ) )
```

Protege syntax:

```
Class: Employee
    SubClassOf:
        Person
    EquivalentTo:
        isEmployedAt some OrgUnit
```

By using a reasoner we may infer that the class Employee contains the individual Martin. The reasoner may even produce an explanation for this:

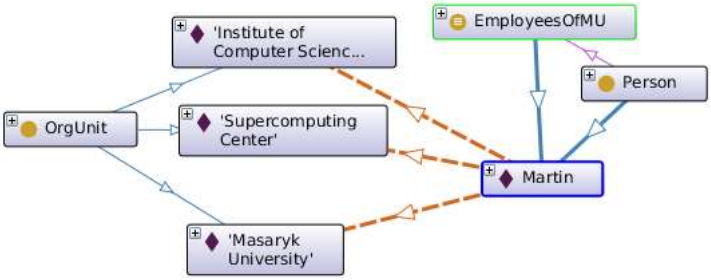




Individual Value Restriction

A class expression can also say that the class contains **individuals** that are **connected by a given property with a given individual**.

In our example, we can define a new class *EmployeesOfMU* as containing individuals that are connected by the property *isEmployedAt* with the individual *MU*, i.e. as those who are employed at MU. A reasoner will find that the class contains the individual *Martin*.



functional syntax:

```
Declaration( Class( :EmployeesOfMU ) )
SubClassOf( :EmployeesOfMU :Person )
EquivalentClasses( :EmployeesOfMU ObjectHasValue( :isEmployedAt :MU ) )
```

Protege syntax:

```
Class: EmployeesOfMU
    SubClassOf:
        Person
    EquivalentTo:
        isEmployedAt value MU
```

Universal Quantification

Universal quantification (in mathematics known by the operator ∀) in OWL is a bit odd because of the **open world assumption** that OWL has.

The existential quantification described above (OWL operator `ObjectSomeValuesFrom()`) as defined in OWL 2 Direct Semantics states "individuals such that there *exists* some individual from the given class connected by the given property", in mathematical notation ObjectSomeValuesFrom(OPE CE) : $\{ x \mid \exists y : (x, y) \in (OPE)^{OP}$ and $y \in (CE)^{C} \}$ where OPE denotes an object property expression, $.^{OP}$ is object property interpretation function, CE denotes a class expression, $.^{C}$ is class interpretation function.

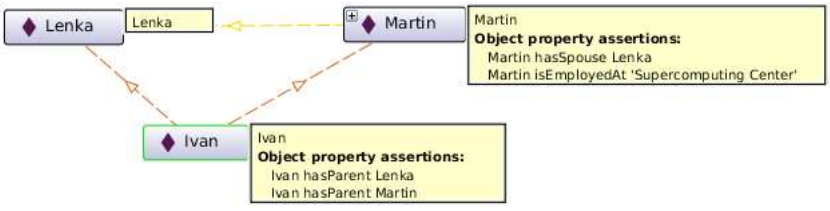
The universal quantification is defined as operator ObjectAllValuesFrom(OPE CE) : $\{ x \mid \forall y : (x, y) \in (OPE)^{OP}$ implies $y \in (CE)^{C} \}$ which means **individuals such that they are *always* connected by the given property only to individuals from the given class**.

The problem with open world assumption is that in the open world an ontology may not contain all information. For example, imagine an ontology that states that the individual Peter has two children, sons John and Paul. We may define a class ManWhoHaveOnlySons as the class of individuals that are connected by property *hasChild* only to individuals from the class *Boy*, i.e. ObjectAllValuesFrom(:hasChild :Boy). However the individual Peter is not necessarily in the class, because Peter may also have a daughter Jane, just the ontology does not contain this information.

Universal quantification in OWL works only together with **cardinality restrictions**, so that if we know that an individual can be connected by a given property to **at most** some number of different individuals, and we know all the individuals, then a conclusion can be drawn.

It is a bit hard to find an example in real life, but here is one. Every person has at most two parents. Let's say that if both parents are of the same nationality, then the person has the same nationality.

Let's create a new individual *Ivan*, which is connected by a new object property *hasParent* to the individuals *Martin* and *Lenka*. The meaning is that Ivan is a child of Martin and Lenka.

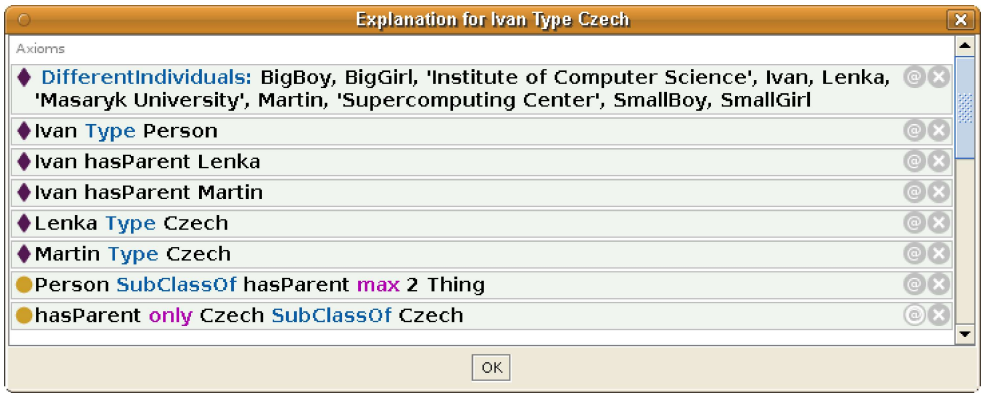



```
Declaration( NamedIndividual( :Ivan ) )
ClassAssertion( :Person :Ivan )
Declaration( ObjectProperty( :hasParent ) )
ObjectPropertyAssertion( :hasParent :Ivan :Martin )
ObjectPropertyAssertion( :hasParent :Ivan :Lenka )
```

We can state that a Person has at most two parents, and define a new class *Czech* containing *Martin* and *Lenka*. The important new thing are the last two axioms - the universal quantification that individuals that have all parents Czech are (a subclass of) Czechs, and that all named individuals in our ontology are different:

```
SubClassOf( :Person ObjectMaxCardinality( 2 :hasParent ) )

Declaration( Class( :Czech ) )
SubClassOf( :Czech :Person )
ClassAssertion( :Czech :Lenka )
ClassAssertion( :Czech :Martin )

SubClassOf( ObjectAllValuesFrom( :hasParent :Czech ) :Czech)
DifferentIndividuals( :BigBoy :BigGirl :ICS :Ivan :Lenka :MU :Martin :SC :SmallBoy :SmallGirl)
```

With these axioms, the conclusion made by a reasoner is **- Ivan is in the class Czech**. He is a Person, so he can have at most two parents, he does have two parents which are different individuals, and both are Czech. Thus no more parents can exist for him, and the universal quantificator can be satistied - he has only Czech parents.



Datatype restrictions

For data properties, we can restrict the values of a data property. For example the axiom

```
EquivalentClasses( :Person DataExactCardinality( 1 :hasAge DatatypeRestriction( xsd:integer xsd:minInclusive "0"^^xsd:integer xsd:maxInclusive "130"^^xsd
```

or in the Manchester syntax

```
Class: Person
  EquivalentTo:
      hasAge exactly 1 xsd:integer[>= 0 , <= 130]
```

defines that individuals in the Person class have exactly one value of the hasAge property that is an integer in the range between 0 and 130.

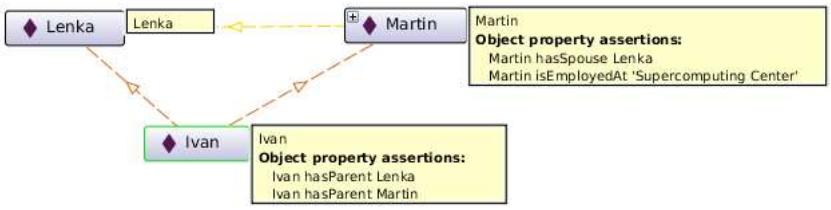
SWRL rules

The OWL 2 language is not able to express all relations. One know example is that it cannot express the relation *child of married parents*, because there is no way in OWL 2 to express the relation between individuals with which an individual has relations.

The expresivity of OWL can be extended by adding SWRL (Semantic Web Rule Language) rules to an ontology. SWRL rules are similar to rules in Prolog or DATALOG languages. In fact, SWRL rules are DATALOG rules with unary predicates for describing classes and data types, binary predicates for properties, and some special built-in n-ary predicates. (See the section SWRL predicates for details)

Protege OWL editor supports SWRL rules, and the reasoners Pellet and Hermit also support SWRL rules.

Let's reuse our example of Ivan, the son of Martin and Lenka. The symmetric property *hasSpouse* connects Martin and Lenka.




```
SymmetricObjectProperty(:hasSpouse)
ObjectPropertyAssertion(:hasSpouse :Martin :Lenka)
ObjectPropertyAssertion( :hasParent :Ivan :Martin )
ObjectPropertyAssertion( :hasParent :Ivan :Lenka )
```

We can add a SWRL rule saying that an individual X from the Person class, which has parents Y and Z such that Y has spouse Z, belongs to a new class *ChildOfMarriedParents*. Such rule is best described in the Protege syntax:

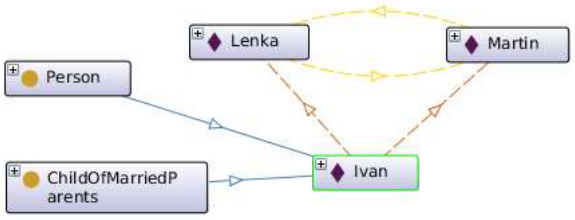
```
Person(?x), hasParent(?x, ?y), hasParent(?x, ?z), hasSpouse(?y, ?z) -> ChildOfMarriedParents(?x)
```

It can be described in functional syntax too:

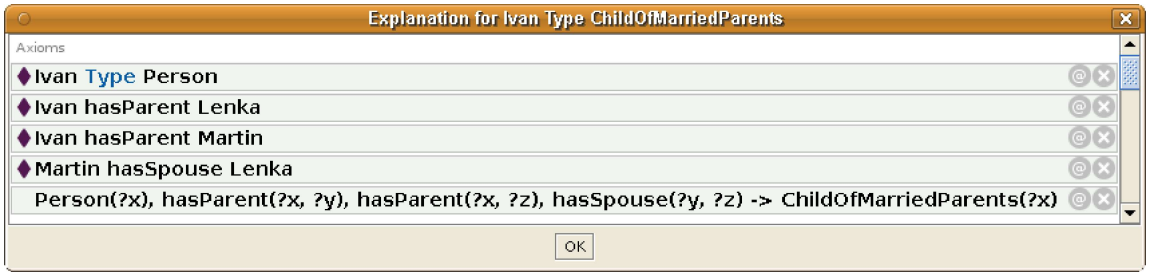
```
Prefix(var:=<urn:swrl#>)

Declaration( Class( :ChildOfMarriedParents ) )
SubClassOf( :ChildOfMarriedParents :Person )

DLSafeRule(
    Body(
        ClassAtom( :Person Variable(var:x))
```

```
            ObjectPropertyAtom( :hasParent Variable(var:x) Variable(var:y) )
            ObjectPropertyAtom( :hasParent Variable(var:x) Variable(var:z) )
            ObjectPropertyAtom( :hasSpouse Variable(var:y) Variable(var:z) )
        )
        Head(
            ClassAtom( :ChildOfMarriedParents Variable(var:x) )
        )
    )
```

When we use the Pellet or Hermit reasoner that supports SWRL rules, it infers that *Ivan* belongs to the class *ChildOfMarriedParents*, and even explains why:




```
ClassAssertion( :ChildOfMarriedParents :Ivan )
```



Different individuals and keys

The OWL's **open world assumption** says that an ontology may not contain all information and thus some information may be unknown. This is why named **individuals with different names may represent the same individual** unless it is explicitely stated that they are different. This is also why we had to specify in the examples above (the set operations and the universal quantification) that the individuals are different.

We can declare the named individuals different in two ways. One is by the DifferentIndividuals() axiom:

```
DifferentIndividuals(:BigBoy :BigGirl :SmallBoy :SmallGirl :ICS :MU :SC :Ivan :Lenka :Martin )
```

However this way is known to cause performance problems for reasoner when the number of individuals is large. The second way how to make individuals different is to use a functional data property with unique values. Functional property can have only one value, and thus makes individuals **different** when their values are different. If the property is also declared as a **key**, it makes individuals with the same value to be the **same** individual.

```
Declaration(DataProperty(:hasId))
FunctionalDataProperty(:hasId)
HasKey( :Person () (:hasId) )
DataPropertyAssertion(:hasId :Lenka  "1234")
DataPropertyAssertion(:hasId :Martin "5648")
```

Using OWL ontology and reasoner from Java code

An ontology is not of much value if it is not used. Fortunately there are already tools for using an ontology in your programming code. I recommend using the following tools:

- OWL API is the Java API used by the Protege OWL editor
- Pellet 2.2 reasoner, which has support for SWRL rules. (Please use version 2.2, because Pellet 2.3 has a bug that causes it to hang on this example.)

I have prepared a Maven project that contains all the sources from this example, dependencies on OWL API from Maven Central repository, and Pellet 2.2 from Berkeley BOP Maven Repository. The Maven project can be compiled and used either from a command line, or from an integrated development environment like IntelliJ IDEA, Eclipse or NetBeans.

Update 2015-02-25: *OWL API has moved to https://github.com/owlcs/owlapi/ and Protege 5 is using newer OWL API 4*

Update 2016-05-06: *I have updated the code examples in the gitHub repository to OWL API 4.2.3*

Clone the Git repository https://github.com/martin-kuba/owl2-swrl-tutorial.

There are examples how to use OWL API, however I show here my own:

```
package cz.makub;

import com.clarkparsia.owlapi.explanation.DefaultExplanationGenerator;
import com.clarkparsia.owlapi.explanation.util.SilentExplanationProgressMonitor;
import com.clarkparsia.pellet.owlapiv3.PelletReasonerFactory;
import org.semanticweb.owlapi.apibinding.OWLManager;
import org.semanticweb.owlapi.io.OWLObjectRenderer;
import org.semanticweb.owlapi.model.*;
```

```
import org.semanticweb.owlapi.reasoner.OWLReasoner;
import org.semanticweb.owlapi.reasoner.OWLReasonerFactory;
import org.semanticweb.owlapi.reasoner.SimpleConfiguration;
import org.semanticweb.owlapi.vocab.OWLRDFVocabulary;
import org.semanticweb.owlapi.vocab.PrefixOWLOntologyFormat;
import uk.ac.manchester.cs.bhig.util.Tree;
import uk.ac.manchester.cs.owl.explanation.ordering.ExplanationOrderer;
import uk.ac.manchester.cs.owl.explanation.ordering.ExplanationOrdererImpl;
import uk.ac.manchester.cs.owl.explanation.ordering.ExplanationTree;
import uk.ac.manchester.cs.owlapi.dlsyntax.DLSyntaxObjectRenderer;

import java.util.*;

/**
 * Example how to use an OWL ontology with a reasoner.
 *
 * Run in Maven with <code>mvn compile; mvn exec:java -Dexec.mainClass=cz.makub.Tutorial</code>
 *
 * @author Martin Kuba makub@ics.muni.cz
 */
public class Tutorial {

    private static final String BASE_URL = "http://acrab.ics.muni.cz/ontologies/tutorial.owl";
    private static OWLObjectRenderer renderer = new DLSyntaxObjectRenderer();

    public static void main(String[] args) throws OWLOntologyCreationException {

        //prepare ontology and reasoner
        OWLOntologyManager manager = OWLManager.createOWLOntologyManager();
        OWLOntology ontology = manager.loadOntologyFromOntologyDocument(IRI.create(BASE_URL));
        OWLReasonerFactory reasonerFactory = PelletReasonerFactory.getInstance();
        OWLReasoner reasoner = reasonerFactory.createReasoner(ontology, new SimpleConfiguration());
        OWLDataFactory factory = manager.getOWLDataFactory();
        PrefixOWLOntologyFormat pm = (PrefixOWLOntologyFormat) manager.getOntologyFormat(ontology);
        pm.setDefaultPrefix(BASE_URL + "#");

        //get class and its individuals
        OWLClass personClass = factory.getOWLClass(":Person", pm);

        for (OWLNamedIndividual person : reasoner.getInstances(personClass, false).getFlattened()) {
            System.out.println("person : " + renderer.render(person));
        }

        //get a given individual
        OWLNamedIndividual martin = factory.getOWLNamedIndividual(":Martin", pm);

        //get values of selected properties on the individual
        OWLDataProperty hasEmailProperty = factory.getOWLDataProperty(":hasEmail", pm);

        OWLObjectProperty isEmployedAtProperty = factory.getOWLObjectProperty(":isEmployedAt", pm);

        for (OWLLiteral email : reasoner.getDataPropertyValues(martin, hasEmailProperty)) {
            System.out.println("Martin has email: " + email.getLiteral());
        }

        for (OWLNamedIndividual ind : reasoner.getObjectPropertyValues(martin, isEmployedAtProperty).getFlattened()) {
            System.out.println("Martin is employed at: " + renderer.render(ind));
        }

        //get Labels
        LocalizedAnnotationSelector as = new LocalizedAnnotationSelector(ontology, factory, "en", "cs");
        for (OWLNamedIndividual ind : reasoner.getObjectPropertyValues(martin, isEmployedAtProperty).getFlattened()) {
            System.out.println("Martin is employed at: '" + as.getLabel(ind) + "'");
        }

        //get inverse of a property, i.e. which individuals are in relation with a given individual
        OWLNamedIndividual university = factory.getOWLNamedIndividual(":MU", pm);
        OWLObjectPropertyExpression inverse = factory.getOWLObjectInverseOf(isEmployedAtProperty);
        for (OWLNamedIndividual ind : reasoner.getObjectPropertyValues(university, inverse).getFlattened()) {
            System.out.println("MU inverseOf(isEmployedAt) -> " + renderer.render(ind));
        }

        //find to which classes the individual belongs
        Set<OWLClassExpression> assertedClasses = martin.getTypes(ontology);
        for (OWLClass c : reasoner.getTypes(martin, false).getFlattened()) {
            boolean asserted = assertedClasses.contains(c);
            System.out.println((asserted ? "asserted" : "inferred") + " class for Martin: " + renderer.render(c));
        }

        //list all object property values for the individual
        Map<OWLObjectPropertyExpression, Set<OWLIndividual>> assertedValues = martin.getObjectPropertyValues(ontology);
        for (OWLObjectProperty objProp : ontology.getObjectPropertiesInSignature(true)) {
            for (OWLNamedIndividual ind : reasoner.getObjectPropertyValues(martin, objProp).getFlattened()) {
                boolean asserted = assertedValues.get(objProp).contains(ind);
                System.out.println((asserted ? "asserted" : "inferred") + " object property for Martin: "
                        + renderer.render(objProp) + " -> " + renderer.render(ind));
            }
        }

        //list all same individuals
        for (OWLNamedIndividual ind : reasoner.getSameIndividuals(martin)) {
            System.out.println("same as Martin: " + renderer.render(ind));
        }

        //ask reasoner whether Martin is employed at MU
        boolean result = reasoner.isEntailed(factory.getOWLObjectPropertyAssertionAxiom(isEmployedAtProperty, martin, university));
        System.out.println("Is Martin employed at MU ? : " + result);
```

```
        //check whether the SWRL rule is used
        OWLNamedIndividual ivan = factory.getOWLNamedIndividual(":Ivan", pm);
        OWLClass chOMPClass = factory.getOWLClass(":ChildOfMarriedParents", pm);
        OWLClassAssertionAxiom axiomToExplain = factory.getOWLClassAssertionAxiom(chOMPClass, ivan);
        System.out.println("Is Ivan child of married parents ? : " + reasoner.isEntailed(axiomToExplain));


        //explain why Ivan is child of married parents
        DefaultExplanationGenerator explanationGenerator =
                new DefaultExplanationGenerator(
                        manager, reasonerFactory, ontology, reasoner, new SilentExplanationProgressMonitor());
        Set<OWLAxiom> explanation = explanationGenerator.getExplanation(axiomToExplain);
        ExplanationOrderer deo = new ExplanationOrdererImpl(manager);
        ExplanationTree explanationTree = deo.getOrderedExplanation(axiomToExplain, explanation);
        System.out.println();
        System.out.println("-- explanation why Ivan is in class ChildOfMarriedParents --");
        printIndented(explanationTree, "");
    }

    private static void printIndented(Tree<OWLAxiom> node, String indent) {
        OWLAxiom axiom = node.getUserObject();
        System.out.println(indent + renderer.render(axiom));
        if (!node.isLeaf()) {
            for (Tree<OWLAxiom> child : node.getChildren()) {
                printIndented(child, indent + "    ");
            }
        }
    }

    /**
     * Helper class for extracting labels, comments and other anotations in preffered languages.
     * Selects the first literal annotation matching the given languages in the given order.
     */
    public static class LocalizedAnnotationSelector {
        private final List<String> langs;
        private final OWLOntology ontology;
        private final OWLDataFactory factory;

        /**
         * Constructor.
         *
         * @param ontology ontology
         * @param factory  data factory
         * @param langs    list of prefered languages; if none is provided the Locale.getDefault() is used
         */
        public LocalizedAnnotationSelector(OWLOntology ontology, OWLDataFactory factory, String... langs) {
            this.langs = (langs == null) ? Arrays.asList(Locale.getDefault().toString()) : Arrays.asList(langs);
            this.ontology = ontology;
            this.factory = factory;
        }

        /**
         * Provides the first label in the first matching language.
         *
         * @param ind individual
         * @return label in one of preferred languages or null if not available
         */
        public String getLabel(OWLNamedIndividual ind) {
            return getAnnotationString(ind, OWLRDFVocabulary.RDFS_LABEL.getIRI());
        }

        @SuppressWarnings("UnusedDeclaration")
        public String getComment(OWLNamedIndividual ind) {
            return getAnnotationString(ind, OWLRDFVocabulary.RDFS_COMMENT.getIRI());
        }

        public String getAnnotationString(OWLNamedIndividual ind, IRI annotationIRI) {
            return getLocalizedString(ind.getAnnotations(ontology, factory.getOWLAnnotationProperty(annotationIRI)));
        }

        private String getLocalizedString(Set<OWLAnnotation> annotations) {
            List<OWLLiteral> literalLabels = new ArrayList<OWLLiteral>(annotations.size());
            for (OWLAnnotation label : annotations) {
                if (label.getValue() instanceof OWLLiteral) {
                    literalLabels.add((OWLLiteral) label.getValue());
                }
            }
            for (String lang : langs) {
                for (OWLLiteral literal : literalLabels) {
                    if (literal.hasLang(lang)) return literal.getLiteral();
                }
            }
            for (OWLLiteral literal : literalLabels) {
                if (!literal.hasLang()) return literal.getLiteral();
            }
            return null;
        }
    }
}
```

Program output:

```
person : BigBoy
person : Lenka
person : SmallGirl
person : SmallBoy
```

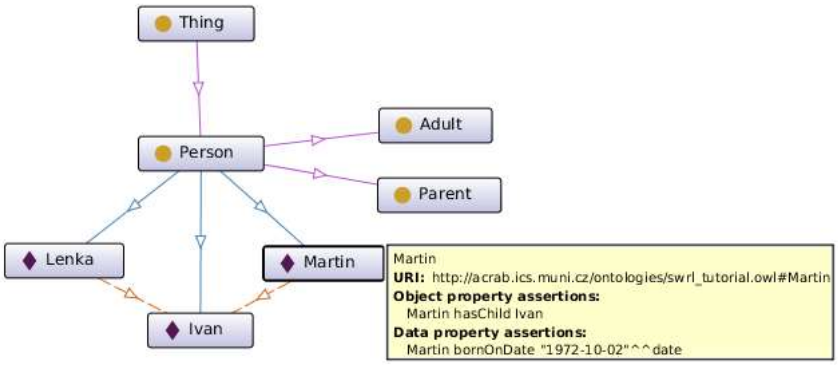
```
person : Martin
person : Ivan
person : BigGirl
Martin has email: makub@ics.muni.cz
Martin is employed at: ICS
Martin is employed at: SC
Martin is employed at: MU
Martin is employed at: 'Institute of Computer Science'
Martin is employed at: 'Supercomputing Center'
Martin is employed at: 'Masaryk University'
MU inverseOf(isEmployedAt) -> Martin
inferred class for Martin: T
asserted class for Martin: Czech
inferred class for Martin: EmployeesOfMU
inferred class for Martin: Person
asserted class for Martin: Student
inferred class for Martin: Employee
asserted object property for Martin: hasSpouse -> Lenka
inferred object property for Martin: isEmployedAt -> ICS
asserted object property for Martin: isEmployedAt -> SC
inferred object property for Martin: isEmployedAt -> MU
same as Martin: Martin
Is Martin employed at MU ? : true
Is Ivan child of married parents ? : true

-- explanation why Ivan is in class ChildOfMarriedParents --
ChildOfMarriedParents(Ivan)
    Person(Ivan)
    hasParent(Ivan, Martin)
    hasParent(Ivan, Lenka)
    hasSpouse(Martin, Lenka)
    ChildOfMarriedParents(?x) ← Person(?x) ∧ hasParent(?x, ?y) ∧ hasParent(?x, ?z) ∧ hasSpouse(?y, ?z)
```

SWRL predicates

SWRL rules can use other predicates than just class or property names. The predicates can be

- **class expressions -** arbitrary class expressions, not just named classes
- **property expressions -** the only operator available in OWL 2 for creating property expresions is inverse of object property, however the same effect can be achieved by exchanging the property arguments, so there is no need to use property expressions in SWRL
- **data range restrictions -** specifies type of data value, like integer, date, union of some XML Schema types, enumerated type
- **sameIndividual** and **differentIndividuals -** for specifying sama and different individuals
- **core SWRL built-ins -** special predicates defined in SWRL proposal which can manipulate data values, for example to add numbers
- **custom SWRL built-ins -** you can define your own built-ins using Java code

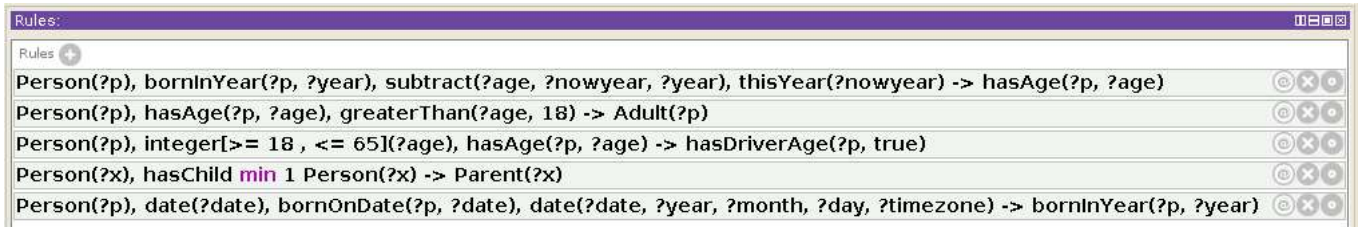
Let's show it on an example. A simple ontology with rules is available at swrl_tutorial.owl. It defines three individuals with their birthdays:




```
Declaration(Class(:Person))
Declaration(ObjectProperty(:hasChild))
Declaration(Class(:Parent))
Declaration(Class(:Adult))
SubClassOf(:Adult :Person)
SubClassOf(:Parent :Person)
Declaration(DataProperty(:bornOnDate))
Declaration(DataProperty(:bornInYear))
Declaration(DataProperty(:hasAge))
FunctionalDataProperty(:hasAge)
Declaration(DataProperty(:hasDriverAge))

Declaration(NamedIndividual(:Martin))
ClassAssertion(:Person :Martin)
DataPropertyAssertion(:bornOnDate :Martin "1972-10-02"^^xsd:date)

Declaration(NamedIndividual(:Lenka))
ClassAssertion(:Person :Lenka)
DataPropertyAssertion(:bornOnDate :Lenka "1975-11-10"^^xsd:date)

Declaration(NamedIndividual(:Ivan))
ClassAssertion(:Person :Ivan)
DataPropertyAssertion(:bornOnDate :Ivan "2006-04-14"^^xsd:date)

ObjectPropertyAssertion(:hasChild :Martin :Ivan)
```

```
ObjectPropertyAssertion(:hasChild :Lenka :Ivan)
```

The ontology also defines some rules:



(Please note that in Protege 4.1 the SWRL rules editor is broken, so these rules were not created in Protege, they were written in a text editor by directly editing the ontology source code. The ontology swrl_tutorial.owl is written in functional syntax that Protege 4.1 can load directly.)

There is a small inconvenience when working with SWRL rules, that their human syntax is not well standardized. The image above is a screenshot from the Protege 4.1, which renders the rules in a variant of Manchester syntax without namespace qualifiers.

SWRL rules with class expressions

The rule in the listing displayed as

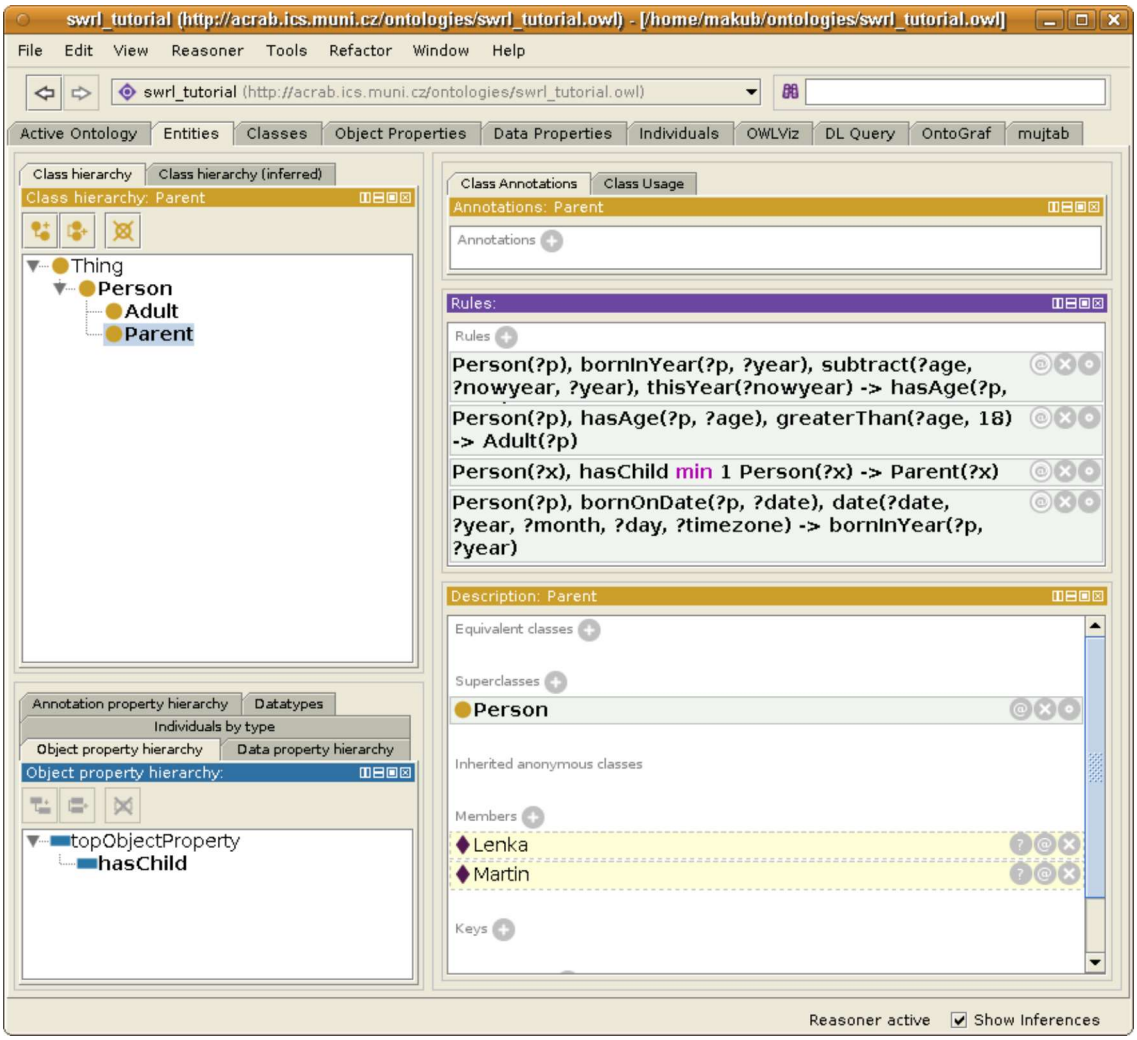
```
Person(?x), hasChild min 1 Person(?x) -> Parent(?x)
```

is in the functional syntax (defined in A Syntax for Rules in OWL2) written as

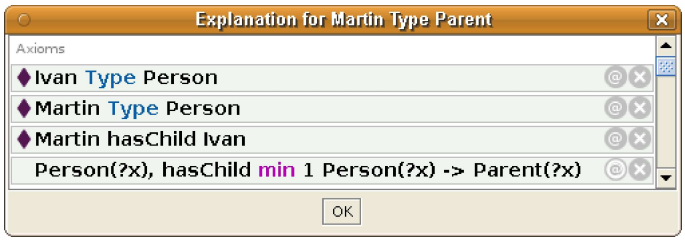
```
DLSafeRule(
    Annotation(rdfs:comment "Rule with class expression")
    Body(
        ClassAtom( :Person Variable(var:x) )
        ClassAtom(
            ObjectMinCardinality( 1 :hasChild :Person )
            Variable(var:x)
        )
    )
    Head(
        ClassAtom( :Parent Variable(var:x) )
    )
)
```

Its meaning is that individuals, that are in the Person class, *and* that have at least one property hasChild with an individual from the class Person, must then be in the Parent class. Or in another words, that persons with at least one child are parents.

When you use the Pellet reasoner, which supports SWRL rules, it will infer that Martin and Lenka are in the class Parent, as can be seen on the following image in the lower right corner:



When you click on the question mark (?) on right of the inferred information, the reasoner even provides information how that information was inferred:



Please note that you can always create a new named class equivalent to a class expression, and use the named class instead of the class expression.

Also note that in this particular example, there is no need to use a SWRL rule, the same can be modeled simply by setting the Parent class as subclass of the "(hasChild min 1 Person)" class expression in OWL. Or by making it equivalent to the class expression, which is a stronger assertion. SWRL rules are really needed only for modeling non-tree structures which cannot be modeled in OWL.

SWRL rules with data range restrictions

The following rule uses a data range restriction:

```
Person(?p), integer[>= 18 , <= 65](?age), hasAge(?p, ?age) -> hasDriverAge(?p, true)
```

The data range restriction is satisfied when the ?age variable has an integer value between 18 and 65 inclusive.

This example shows a complex data range restriction with facets, a simpler example would be `integer(?x)` or `xsd:date(?y)` which restrict the type without using facets.

For a full descrition of data ranges see OWL 2 Data Ranges. An example data range using union, intersection, complement and facets in the same time would be in Manchester syntax:

```
((integer[>=1,<=2] or integer[>5,<7]) and not ({0}))(?y)
```

and the same in funtional syntax:

```
DataRangeAtom(
    DataIntersectionOf(
        DataUnionOf(
            DatatypeRestriction( xsd:integer xsd:minInclusive "1"^^xsd:integer xsd:maxInclusive "2"^^xsd:integer )
            DatatypeRestriction( xsd:integer xsd:minExclusive "5"^^xsd:integer xsd:maxExclusive "7"^^xsd:integer )
        )
        DataComplementOf(
            DataOneOf( "0"^^xsd:integer )
        )
    )
    Variable(var:y)
)
```

SWRL rules with core built-ins

The SWRL proposal defines also some special predicates, which can be used to manipulate data values. The predicates are called SWRL core built-ins, and are identified by IRIs in the swlrb: namespace. Only the Pellet reasoner as of the time of writting supports them, and it does not support all of them (see Which SWRL builtins does Pellet support? for details).

The following rules from the listing use the core built-ins, they would be most correctly written as:

```
Person(?p), hasAge(?p, ?age), swrlb:greaterThan(?age, 18) -> Adult(?p)
Person(?p), bornOnDate(?p, ?date), xsd:date(?date), swrlb:date(?date, ?year, ?month, ?day, ?timezone) -> bornInYear(?p, ?year)
```

The first of these two rules says that persons who have age higher than 18 are adults. The second rule takes the data value of the bornOnDate property, which must be of xsd:date type, splits it into pieces, and adds the year part as the value of the bornInYear property for the same person.

When the reasoner is used, the second rule is used:

There are some restrictions in the use of built-ins. In the Pellet reasoner, they can be used only in the body of a rule, not in the head. And they can be used only for data values, not for object values. Some built-ins, like the swrlb:date(), can be used with both bound and unbound variables, while other, like the swrlb:greaterThan(), can be used only for bound variables.

SWRL rules with custom built-ins

You can even define your own SWRL built-ins. As of the time of writing, only the Pellet reasoner allows this. There is some misleading old documentation at SWRLBuiltInBridge which was written for the SWRLTab available only in the old Protege 3 which does not support OWL2, but is not usable in the newer Protege 4.1 or in Java programs using the newer OWL API 3.

Thanks to the How to extend Pellet2.2.2's SWRL rule support with your custom built-in ? page I have found how to define my own custom built-ins for use with OWL API 3.

The rule

```
Person(?p), bornInYear(?p, ?year), my:thisYear(?nowyear), swrlb:subtract(?age, ?nowyear, ?year) -> hasAge(?p, ?age)
```

uses the my:thisYear custom built-in to bind the integer value of the current year to the ?nowyear variable, and then uses the swrlb:subtract core built-in to compute the person's age in years, then it sets the result as the value of the hasAge property. The rule can be used in a Java program:

```
package cz.makub;

import aterm.ATermAppl;
import com.clarkparsia.pellet.owlapiv3.PelletReasonerFactory;
import com.clarkparsia.pellet.rules.builtins.BuiltInRegistry;
import com.clarkparsia.pellet.rules.builtins.GeneralFunction;
import com.clarkparsia.pellet.rules.builtins.GeneralFunctionBuiltIn;
import org.mindswap.pellet.ABox;
import org.mindswap.pellet.Literal;
import org.mindswap.pellet.utils.ATermUtils;
import org.semanticweb.owlapi.apibinding.OWLManager;
import org.semanticweb.owlapi.io.OWLObjectRenderer;
import org.semanticweb.owlapi.model.*;
import org.semanticweb.owlapi.reasoner.OWLReasoner;
import org.semanticweb.owlapi.reasoner.OWLReasonerFactory;
import org.semanticweb.owlapi.reasoner.SimpleConfiguration;
import org.semanticweb.owlapi.vocab.PrefixOWLOntologyFormat;
import uk.ac.manchester.cs.owlapi.dlsyntax.DLSyntaxObjectRenderer;

import java.text.SimpleDateFormat;
import java.util.Calendar;
```

```
import java.util.Map;
import java.util.Set;

import static org.mindswap.pellet.utils.Namespaces.XSD;

/**
 * Example of Pellet custom SWRL built-in.
 *
 * Run in Maven with <code>mvn exec:java -Dexec.mainClass=cz.makub.SWRLBuiltInsTutorial</code>
 *
 * @author Martin Kuba makub@ics.muni.cz
 */
public class SWRLBuiltInsTutorial {

    /**
     * Implementation of a SWRL custom built-in.
     */
    private static class ThisYear implements GeneralFunction {

        public boolean apply(ABox abox, Literal[] args) {
            Calendar calendar = Calendar.getInstance();
            String year = new SimpleDateFormat("yyyy").format(calendar.getTime());
            if (args[0] == null) {
                //variable not bound, fill it with the current year
                args[0] = abox.addLiteral(ATermUtils.makeTypedLiteral(year, XSD + "integer"));
                return args[0] != null;
            } else {
                //variable is bound, compare its value with the current year
                return year.equals(args[0].getLexicalValue());
            }
        }

        public boolean isApplicable(boolean[] boundPositions) {
            //the built-in is applicable for one argument only
            return boundPositions.length == 1;
        }

    }

    private static final String DOC_URL = "http://acrab.ics.muni.cz/ontologies/swrl_tutorial.owl";

    public static void main(String[] args) throws OWLOntologyCreationException {
        //register my built-in
        BuiltInRegistry.instance.registerBuiltIn("urn:makub:builtIn#thisYear", new GeneralFunctionBuiltIn(new ThisYear()));
        //initialize ontology and reasoner
        OWLOntologyManager manager = OWLManager.createOWLOntologyManager();
        OWLOntology ontology = manager.loadOntologyFromOntologyDocument(IRI.create(DOC_URL));
        OWLReasonerFactory reasonerFactory = PelletReasonerFactory.getInstance();
        OWLReasoner reasoner = reasonerFactory.createReasoner(ontology, new SimpleConfiguration());
        OWLDataFactory factory = manager.getOWLDataFactory();
        PrefixOWLOntologyFormat pm = manager.getOntologyFormat(ontology).asPrefixOWLOntologyFormat();
        //use the rule with the built-in to infer data property values
        OWLNamedIndividual martin = factory.getOWLNamedIndividual(":Martin", pm);
        listAllDataPropertyValues(martin,ontology,reasoner);

        OWLNamedIndividual ivan = factory.getOWLNamedIndividual(":Ivan", pm);
        listAllDataPropertyValues(ivan,ontology,reasoner);
    }

    public static void listAllDataPropertyValues(OWLNamedIndividual individual,OWLOntology ontology,OWLReasoner reasoner) {
        OWLObjectRenderer renderer = new DLSyntaxObjectRenderer();
        Map<OWLDataPropertyExpression, Set<OWLLiteral>> assertedValues = individual.getDataPropertyValues(ontology);
        for (OWLDataProperty dataProp : ontology.getDataPropertiesInSignature(true)) {
            for (OWLLiteral literal : reasoner.getDataPropertyValues(individual, dataProp)) {
                Set<OWLLiteral> literalSet = assertedValues.get(dataProp);
                boolean asserted = (literalSet!=null&&literalSet.contains(literal));
                System.out.println((asserted ? "asserted" : "inferred") + " data property for "+renderer.render(individual)+" : "
                        + renderer.render(dataProp) + " -> " + renderer.render(literal));
            }
        }
    }
}
```

The program when run prints the inferred values for the bornInYear, hasAge and hasDriverAge properties:

```
asserted data property for Martin : bornOnDate -> 1972-10-02
inferred data property for Martin : hasAge -> 39
inferred data property for Martin : bornInYear -> 1972
inferred data property for Martin : hasDriverAge -> true
asserted data property for Ivan : bornOnDate -> 2006-04-14
inferred data property for Ivan : hasAge -> 5
inferred data property for Ivan : bornInYear -> 2006
```

Please note that the rules worked in cooperation. First the rule with the core built-in computed the integer value of the bornInYear property, then the rule with the custom built-in computed the integer value of the hasAge property, and at last the rule with the faceted data range assigned the boolean value of the hasDriverAge property. Unfortunately I do not know if it is possible to use the custom built-in inside of Protege 4.1.

SWRL rules with custom built-ins for individuals

The SWRL specification allows only data values as arguments for built-ins. However the Pellet reasoner **is** able to process rules with builtins that work with individuals. Just there is no documentation for that. The only information available is from an email by Brandon Ibach and the poorly documented source of the classes in the `com.clarkparsia.pellet.rules.builtins` package.

I have created a class CustomSWRLBuiltin.java that is similar to the Pellet's GeneralFunctionBuiltIn class, but allows also individuals, not only literals. It provides an interface `CustomSWRLFunction` that should be implemented to provide a built-in that can accept both literals and individuals.

An example of a built-in that works with individuals is a built-in that takes as input an individual and a separator string, obtains the IRI of the individual, splits the IRI into two parts at the position of the separator string, and binds these two IRI parts into variables:

```
package cz.makub;

import cz.makub.swrl.CustomSWRLBuiltin;
import com.clarkparsia.pellet.owlapiv3.PelletReasonerFactory;
import com.clarkparsia.pellet.rules.builtins.BuiltInRegistry;
import org.mindswap.pellet.ABox;
import org.mindswap.pellet.Node;
import org.mindswap.pellet.utils.ATermUtils;
import org.semanticweb.owlapi.apibinding.OWLManager;
import org.semanticweb.owlapi.io.OWLObjectRenderer;
import org.semanticweb.owlapi.model.*;
import org.semanticweb.owlapi.reasoner.OWLReasoner;
import org.semanticweb.owlapi.reasoner.OWLReasonerFactory;
import org.semanticweb.owlapi.reasoner.SimpleConfiguration;
import org.semanticweb.owlapi.vocab.PrefixOWLOntologyFormat;
import uk.ac.manchester.cs.owlapi.dlsyntax.DLSyntaxObjectRenderer;

import java.util.Map;
import java.util.Set;

import static org.mindswap.pellet.utils.Namespaces.XSD;

/**
 * Example of a Pellet SWRL built-in that works with both Individuals and data literals.
 *
 * Run in Maven with <code>mvn exec:java -Dexec.mainClass=cz.makub.IndividualSWRLBuiltinTutorial</code>
 *
 * @author Martin Kuba makub@ics.muni.cz
 */
public class IndividualSWRLBuiltinTutorial {

    /**
     * The built-in implementation.
     */
    public static class IRIparts implements CustomSWRLBuiltin.CustomSWRLFunction {

        @Override
        public boolean isApplicable(boolean[] boundPositions) {
            //applicable only to 4 arguments, two bound and two unbound
            return boundPositions.length == 4 && boundPositions[0] && boundPositions[1] && !boundPositions[2] && !boundPositions[3];
        }

        @Override
        public boolean apply(ABox abox, Node[] args) {
            //accepts IRIparts(individual,separator string,unbound variable,unbound variable)
            if (!args[0].isIndividual() || !args[1].isLiteral() || args[2] != null || args[3] != null) return false;
            //get the IRI of the individual in the first argument
            String iri = args[0].getNameStr();
            //get the string value of the second argument
            String separator = ATermUtils.getLiteralValue(args[1].getTerm());
            //split the IRI at the separator
            int idx = iri.indexOf(separator);
            if (idx == -1) return false;
            String prefix = iri.substring(0, idx);
            String id = iri.substring(idx + separator.length());
            //bind the third and fourth arguments to the IRI parts
            args[2] = abox.addLiteral(ATermUtils.makeTypedLiteral(prefix, XSD + "string"));
            args[3] = abox.addLiteral(ATermUtils.makeTypedLiteral(id, XSD + "string"));
            return true;
        }
    }

    //a simple example ontology
    private static final String DOC_URL = "http://acrab.ics.muni.cz/ontologies/swrl_tutorial_ind.owl";

    public static void main(String[] args) throws OWLOntologyCreationException {
        //register my built-in implementation
        BuiltInRegistry.instance.registerBuiltIn("urn:makub:builtIn#IRIparts", new CustomSWRLBuiltin(new IRIparts()));
        //initialize ontology and reasoner
        OWLOntologyManager manager = OWLManager.createOWLOntologyManager();
        OWLOntology ontology = manager.loadOntologyFromOntologyDocument(IRI.create(DOC_URL));
        OWLReasonerFactory reasonerFactory = PelletReasonerFactory.getInstance();
        OWLReasoner reasoner = reasonerFactory.createReasoner(ontology, new SimpleConfiguration());
        OWLDataFactory factory = manager.getOWLDataFactory();
        PrefixOWLOntologyFormat pm = (PrefixOWLOntologyFormat) manager.getOntologyFormat(ontology);
        //print the SWRL rule
        listSWRLRules(ontology, pm);
        //use the rule with the built-in to infer property values
        OWLNamedIndividual martin = factory.getOWLNamedIndividual(":Martin", pm);
        listAllDataPropertyValues(martin, ontology, reasoner);
    }

    public static void listSWRLRules(OWLOntology ontology, PrefixOWLOntologyFormat pm) {
        OWLObjectRenderer renderer = new DLSyntaxObjectRenderer();
        for (SWRLRule rule : ontology.getAxioms(AxiomType.SWRL_RULE)) {
            System.out.println(renderer.render(rule));
        }
    }

    public static void listAllDataPropertyValues(OWLNamedIndividual individual, OWLOntology ontology, OWLReasoner reasoner) {
        OWLObjectRenderer renderer = new DLSyntaxObjectRenderer();
```

```
        Map<OWLDataPropertyExpression, Set<OWLLiteral>> assertedValues = individual.getDataPropertyValues(ontology);
        for (OWLDataProperty dataProp : ontology.getDataPropertiesInSignature(true)) {
            for (OWLLiteral literal : reasoner.getDataPropertyValues(individual, dataProp)) {
                Set<OWLLiteral> literalSet = assertedValues.get(dataProp);
                boolean asserted = (literalSet != null && literalSet.contains(literal));
                System.out.println((asserted ? "asserted" : "inferred") + " data property for " + renderer.render(individual) + " : "
                        + renderer.render(dataProp) + " -> " + renderer.render(literal));
            }
        }
    }
}
```

The ontology contains just an individual and the following rule that uses the custom built-in `IRIparts` in its body to split the IRI of each person at the point of the # character. In the head, the rule has two data property assertions just to use the produced string values:

```
Person(?p), IRIparts(?p,"#"^^xsd:string,?q,?r) -> hasIRIprefix(?p, ?q), hasIRIid(?p, ?r)
```

When run, the program should print:

```
hasIRIid(?p, ?r) ∧ hasIRIprefix(?p, ?q) ← Person(?p) ∧ urn:makub:builtIn#IRIparts((?p) , (#) , (?q) , (?r))
inferred data property for Martin : hasIRIprefix -> http://acrab.ics.muni.cz/ontologies/swrl_tutorial_ind.owl
inferred data property for Martin : hasIRIid -> Martin
```

Tips, tricks and gotchas

Here I collect my findings from working with OWL+SWRL ontologies.

Property domains and ranges

A surprising feature of OWL properties are their domain and ranges. For those who undertook some course in mathematics, the behavior is counter-intuitive. If you define a property domain in OWL, it is not a constraint on the individuals that may appear as the property's source. Instead, it forces any individual which has this property to belong to the domain.

For example, let's define a property *olderThan* with domain *Person*, and assert *Martin olderThan Lenka*. Then either by mistake or because it is tempting to reuse the property, we assert *Pyramids olderThan The_Great_Wall_of_China*. Instead of an incosistent ontology we get a result that *Pyramids* are a *Person*.

This counter-intuitive behavior of OWL properies is mentioned in OWL 2 Primer,chapter 4.8 Datatypes, it is better to think about property domains and ranges in the way suggested in 4.6 Domain and Range Restrictions, i.e. as adding implicit additional information, e.g. that every individual in the range of a :hasWife property must be a woman.

Reflexive properties

A reflexive relation in mathematics is a binary relation on a set for which every element is related to itself. One would expect that the reflexive property in OWL 2 does the same on its domain. However it's not the case. A reflexive relation in OWL 2 makes **every individual** related to itself, its domain is *owl:Thing*. If you define a domain for a reflexive property, you **force the domain to be equivalent to *owl:Thing***. The reason is the definition of ReflexiveObjectProperty semantics, which says

```
∀ x : x ∈ ΔI implies ( x , x ) ∈ (OPE)OP
```

where ΔI is "object domain", not the property domain.

What you need to do instead is to define the reflexivity only on the domain. If you look up the Reflexive Object Properties definition, you may notice that it is just a shortcut for `SubClassOf( owl:Thing ObjectHasSelf( OPE ) )`. So we can do the same for any class other than *owl:Thing*. Thus we may define for example that only *roles* are *equalTo* themselves:

```
SubClassOf( :Role ObjectHasSelf( :equalTo ) )
```

Negation

While there are direct constructs to express negative object and data property assertions, for example

```
NegativeObjectPropertyAssertion( :hasSpouse :Martin :Peter)
NegativeDataPropertyAssertion( :hasEmail :Martin "president@whitehouse.gov")
```

if you want to express that an individual does not belong to a class, you have to express it as that the individual belongs to the complement of the class:

```
ClassAssertion( ObjectComplementOf( :BadGuy ) :Martin )
```

Even more difficult is to express a "closed" world, because OWL has the "Open World Assumption". For example, if you assert that "Bob has licence for Matlab", OWA says that there may be other people with the licence, just we do not know who they are. So if you want to express that *only Bob has a licence for Matlab*, you can express it as (in Manchester and functional syntaxes):

```
Person and (not ({Bob})) EquivalentTo hasLicence max 0 ({Matlab})

EquivalentClasses(
    Annotation(rdfs:comment "Only Bob has a licence for Matlab")
    ObjectMaxCardinality( 0 :hasLicence ObjectOneOf(:Matlab) )
    ObjectIntersectionOf( ObjectComplementOf(ObjectOneOf(:Bob)) :Person )
)
```

which is saying "*Persons other than Bob have at most zero licences for Matlab*". The `ObjectOneOf()` class expression, which defines a class by enumerating all its members, is the only way how to close the world.

If you want to have a rule with a negation of a property, you can also do it with cardinality restriction (in Manchester and functional syntaxes):

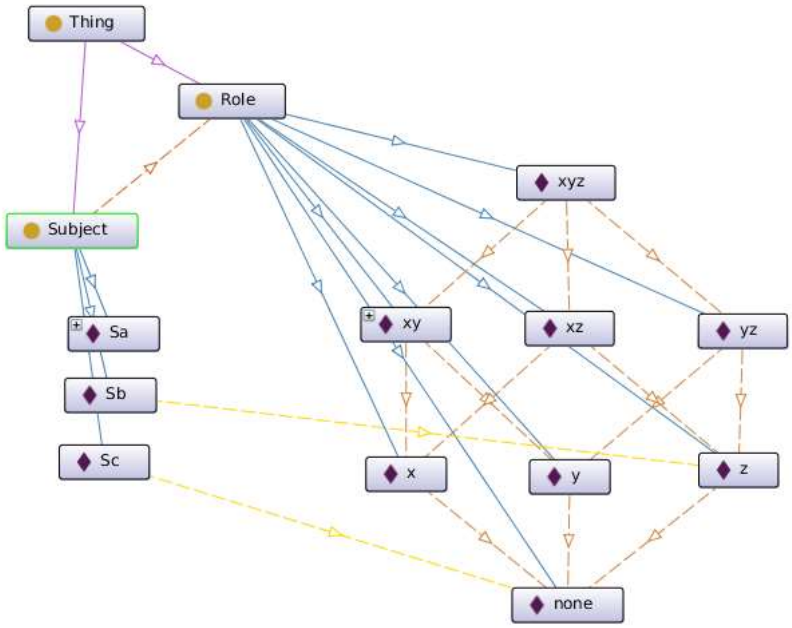
```
Person(?p),(locatedIn max 0 Room)(?p) -> PersonNotInRoom(?p)
```

```
DLSafeRule(
    Body(
      ClassAtom( :Person Variable(var:p) )
      ClassAtom( ObjectMaxCardinality( 0 :locatedIn :Room ) Variable(var:p) )
    )
    Head(
      ClassAtom( :PersonNotInRoom Variable(var:p) )
    )
)
```

Partial ordering

Sometimes one needs to model a relation that represents partial ordering. There are no primitives for that in OWL 2, but partial ordering relation can be modelled by creating a property that is reflexive, transitive and antisymmetric.

An example of such property is the property `:greaterOrEqual` from the ontology poset.owl that is visualised on the following image:



The trick is in creating a property :greaterOrEqual that has two subproperties - :equalTo that is symmetric and :greaterThan that is transitive:

```
Declaration(ObjectProperty(:equalTo))
Declaration(ObjectProperty(:greateOrEqual))
Declaration(ObjectProperty(:greaterThan))
SubClassOf(:Role ObjectHasSelf(:equalTo))
TransitiveObjectProperty(:greaterThan)
SubObjectPropertyOf(:equalTo :greateOrEqual)
SubObjectPropertyOf(:greaterThan :greateOrEqual)
```

Limits of OWL2 and SWRL

In knowing a technology, it may be helpful to know where its limits are. In OWL 2 and SWRL, the limits are imposed mainly by the underlaying logic.

I assume that you have heard about mathematical logic, at least about propositional logic and first order predicate logic.

To refresh your memory, **propositional logic** is the logic whose formulae are made of **atomic propositions** like A, B, having always one of the values **true** or **false**, and **logical connectives** like **negation** (¬A), **and** (A∧B), **or** (A∨B) and **implication** (A→B). Propositional logic is sound (only deriving correct results), complete (able to derive any logically valid formula) and decidable (the algorithms for deciding whether a formula is valid end in finite time).

Predicate logic is the logic which adds **predicates** (like P(x,y)) which represent relations, i.e. produce **true** or **false** for a combination of values of the terms x and y; **quantifiers**: existential ∃ ("there exists") and universal ∀ ("for all"); and **terms** made of variables and functions, like f(x), g(y,z). Thus predicate logic can form formulas like ∀x∃y(P(x)→Q(f(y))).

First order predicate logic is the logic where the quantifiers can range only over elements of sets. In higher order logics, quantifiers can range over sets, functions and other objects. So, for example, the sentence that "every set of real numbers has a minimum" cannot be expresed in first order logic, because the quantification ranges over sets, not set elements.

First order predicate logic is sound and complete, however it is **not decidable**. It is semidecidable, valid formulas can be proven, but non-valid formulas may need infinite time to construct a counter-example of infinite size.

There are known algorithms that can prove valid theorems in first order predicate logic, namely the tableaux algorithm, however if the theorem is not valid, the algorithm may not end in finite time.

The OWL language is based on description logics (DL) , which is a family of logics designed to be as expressive as possible while retaining decidability. The OWL version 1 is based on the description logic $\mathrm{SHOIN}^{(D)}$, and OWL version 2 is based on the DL $\mathrm{SROIQ}^{(D)}$.

The OWL 2 DL is a decidable fragment of first order predicate logic, with some decidable extensions that go beyond first order logic (see Relationship with other logic for details).

It is known that OWL 1 cannot express the *uncle* relation, which is a chain of relations *parent* and *sibling*. OWL 2 can express uncle using property chains, however it still cannot express relations between individuals referenced by properties. Namely OWL 2 cannot express the *child of married parents* concept because it cannot express the relationship between parents of the individual (see A better uncle for OWL article).

Using SWRL, we can express even the *child of married parents* concept. However arbitrary SWRL rules would lead to undecidability, so only so-called **DL-safe** rules are implemented in reasoners. DL-safe rules are rules applied only to named individuals, they **do not apply** to individuals that are not named but are known to exist. See What are DL-Safe SWRL Rules? for details.

Being a fragment of first order predicate logic, the DL cannot express the following:

- fuzzy expressions - "It **often** rains in autumn."
- non-monotonicity - "Birds fly, penguin is a bird, but penguin does not fly."
- propositional attitudes - "Eve **thinks** that 2 is not a prime number." (It is true that she thinks it, but what she thinks is not true.)
- modal logic
  - possibility and necessity - "It is **possible** that it will rain today."
  - epistemic modalities - "Eve **knows** that 2 is a prime number."
  - temporal logic - "I am **always** hungry."
  - deontic logic - "You **must** do this."

It is worth mentioning that there is a logic available which can express anything we may say - the Transparent Intensional Logic. However there are no reasoners for TIL.