

DR-DEVICE: A Defeasible Logic System for the Semantic Web

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Abstract. This paper presents DR-DEVICE, a system for defeasible reasoning on the Web. Defeasible reasoning is a rule-based approach for efficient reasoning with incomplete and inconsistent information. Such reasoning is, among others, useful for ontology integration, where conflicting information arises naturally; and for the modeling of business rules and policies, where rules with exceptions are often used. In this paper we describe these scenarios in more detail along with the implementation of the DR-DEVICE system, which is capable of reasoning about RDF data over multiple Web sources using defeasible logic rules. The system is implemented on top of CLIPS production rule system and builds upon R-DEVICE, an earlier deductive rule system over RDF data that also supports derived attribute and aggregate attribute rules. Rules can be expressed either in a native CLIPS-like language, or in an extension of the OO-RuleML syntax. The operational semantics of defeasible logic are implemented through compilation into the generic rule language of R-DEVICE. The paper includes a use case of a semantic web broker that reasons defeasibly about renting apartments based on buyer's requirements (expressed RuleML defeasible logic rules) and seller's advertisements (expressed in RDF).

1. Introduction

The development of the Semantic Web [14] proceeds in layers, each layer being on top of other layers. At present, the highest layer that has reached sufficient maturity is the ontology layer in the form of the description logic based languages of DAML+OIL [18] and OWL [20].

The next step in the development of the Semantic Web will be the logic and proof layers, and rule systems appear to lie in the mainstream of such activities. Moreover, rule systems can also be utilized in ontology languages. So, in general rule systems can play a twofold role in the Semantic Web initiative: (a) they can serve as extensions of, or alternatives to, description logic based ontology languages; and (b) they can be used to develop declarative systems on top of (using) ontologies. Reasons why rule systems are expected to play a key role in the further development of the Semantic Web include the following:

1. Seen as subsets of predicate logic, monotonic rule systems (Horn logic) and description logics are orthogonal; thus they provide additional expressive power to ontology languages.
2. Efficient reasoning support exists to support rule languages.
3. Rules are well known in practice, and are reasonably well integrated in mainstream information technology.

Possible interactions between description logics and monotonic rule systems were studied in [26]. Based on that work and on previous work on hybrid reasoning [28] it appears that the best one can do at present is to take the intersection of the expressive power of Horn logic and description logics; one way to view this intersection is the Horn-definable subset of OWL.

This paper is devoted to a different problem, namely conflicts among rules. Here we just mention the main sources of such conflicts, which are further expanded in section 2. At the ontology layer: (a) default inheritance within ontologies, (b) ontology merging; and at the logic and reasoning layers: (a) rules with exceptions as a natural representation of business rules, (b) reasoning with incomplete information.

Defeasible reasoning is a simple rule-based approach to reasoning with incomplete and inconsistent information. It can represent facts, rules, and priorities among rules. This reasoning family comprises defeasible logics ([35], [6]) and Courteous Logic Programs [24]. The main advantage of this approach is the combination of two desirable features: enhanced representational capabilities allowing one to reason with incomplete and contradictory information, coupled with low computational complexity compared to mainstream nonmonotonic reasoning.

In this paper we report on the implementation of a defeasible reasoning system for reasoning on the Web, called DR-DEVICE. Its main characteristics are the following:

- Its user interface is compatible with RuleML [15], the main standardization effort for rules on the Semantic Web.
- It is based on a CLIPS-based implementation of deductive rules ([10], [11]). The core of the system consists of a translation of defeasible knowledge into a set of deductive rules, including derived and aggregate attributes. However, the implementation is declarative because it interprets the not operator using Well-Founded Semantics [21].

2. Conflicting Rules on the Semantic Web

In this section we describe in more detail certain scenarios that justify the need for defeasible reasoning on the Semantic Web.

Reasoning with Incomplete Information. In [4] a scenario is described where business rules have to deal with incomplete information: in the absence of certain information some assumptions have to be made which lead to conclusions not supported by classical predicate logic. In many applications on the Web such assumptions must be made because other players may not be able (e.g. due to communication problems) or willing (e.g. because of privacy or security concerns) to provide information. This is the classical case for the use of nonmonotonic knowledge representation and reasoning [33].

Rules with Exceptions. Rules with exceptions are a natural representation for policies and business rules [5]. And priority information is often implicitly or explicitly available to resolve conflicts among rules. Potential applications include security policies ([9], [29]), business rules [2], personalization, brokering, bargaining, and automated agent negotiations [22].

Default Inheritance in Ontologies. Default inheritance is a well-known feature of certain knowledge representation formalisms. Thus it may play a role in ontology languages, which currently do not support this feature. In [23] some ideas are presented for possible uses of default inheritance in ontologies. A natural way of representing default inheritance is rules with exceptions, plus priority information. Thus, non-monotonic rule systems can be utilized in ontology languages.

Ontology Merging. When ontologies from different authors and/or sources are merged, contradictions arise naturally. Predicate logic based formalisms, including all current Semantic Web languages, cannot cope with inconsistencies. If rule-based ontology languages are used (e.g. DLP [26]) and if rules are interpreted as defeasible (that is, they may be prevented from being applied even if they can fire) then we arrive at nonmonotonic rule systems. A skeptical approach, as adopted by defeasible reasoning, is sensible because it does not allow for contradictory conclusions to be drawn. Moreover, priorities may be used to resolve some conflicts among rules, based on knowledge about the reliability of sources or on user input). Thus, nonmonotonic rule systems can support ontology integration.

3. An Introduction to Defeasible Logics

The basic characteristics of defeasible logics are:

- Defeasible logics are rule-based, without disjunction.
- Classical negation is used in the heads and bodies of rules, but negation-as-failure is not used in the object language (it can easily be simulated, if necessary [6], [8]).
- Rules may support conflicting conclusions.
- The logics are skeptical in the sense that conflicting rules do not fire. Thus consistency is preserved.
- Priorities on rules may be used to resolve some conflicts among rules.
- The logics take a pragmatic view and have low computational complexity.

A *defeasible theory* D is a couple $(R, >)$ where R a finite set of rules, and $>$ a superiority relation on R . In expressing the proof theory we consider only propositional rules. Rules containing free variables are interpreted as the set of their variable-free instances.

There are three kinds of rules: *Strict rules* are denoted by $A \rightarrow p$, and are interpreted in the classical sense: whenever the premises are indisputable then so is the conclusion. An example of a strict rule is “Professors are faculty members”. Written formally: $\text{professor}(x) \rightarrow \text{faculty}(x)$. Inference from strict rules only is called *definite inference*. Strict rules are intended to define relationships that are definitional in nature, for example ontological knowledge.

Defeasible rules are denoted by $A \Rightarrow p$, and can be defeated by contrary evidence. An example of such a rule is $\text{professor}(X) \Rightarrow \text{tenured}(X)$ which reads as follows: “Professors are typically tenured”.

Defeaters are denoted as $A \sim> p$ and are used only to prevent some conclusions, not to actively support conclusions. An example of such a defeater is $\text{assistant-Prof}(X) \sim> \neg\text{tenured}(X)$ which reads as follows: “Assistant professors may be not tenured”.

A *superiority relation* on R is an acyclic relation $>$ on R (that is, the transitive closure of $>$ is irreflexive). When $r_1 > r_2$, then r_1 is called *superior* to r_2 , and r_2 *inferior* to r_1 . This expresses that r_1 may override r_2 . For example, given the defeasible rules

```
r1: visiting-professor(X) => professor(X)
r2: professor(X) => tenured(X)
r3: visiting-professor(X) => ¬tenured(X)
```

no conclusive decision can be made about whether a visiting professor is tenured, because rules r_2 and r_3 contradict each other. But if we introduce a superiority relation $>$ with $r_3 > r_2$, then we can indeed conclude that a visiting professor is not tenured.

A formal definition of the proof theory is found in [6]. A model theoretic semantics is found in [32].

4. The DR-DEVICE System

The DR-DEVICE system consists of two major components (Fig. 1): the RDF loader/translator and the rule loader/translator. The former accepts from the latter (or the user) requests for loading specific RDF documents. The RDF triple loader downloads the RDF document from the Internet and uses the ARP parser [34] to translate it to triples in the N-triple format. Both the RDF/XML and N-triple files are stored locally for future reference. Furthermore, the RDF document is recursively scanned for namespaces which are also parsed using the ARP parser. The rationale for translating namespaces is to obtain a complete RDF Schema in order to minimize the number of OO schema redefinitions. Fetching multiple RDF schema files will aggregate multiple RDF-to-OO schema translations into a single OO schema redefinition. Namespace resolution is not guaranteed to yield an RDF schema document; therefore, if the namespace URI is not an RDF document, then the ARP parser will not produce triples and DR-DEVICE will make assumptions, based on the RDF semantics [27], about non-resolved properties, resources, classes, etc.

All N-triples are loaded into memory, while the resources that have a `URI#anchorID` or `URI/anchorID` format are transformed into a `ns:anchorID` format if URI belongs to the initially collected namespaces, in order to save memory space. The transformed RDF triples are fed to the RDF triple translator which maps them into COOL objects, according to the mapping scheme in section 4.1. Notice that as RDF triples are mapped to objects they get deleted.

The rule loader accepts from the user a URI (or a local file name) that contains a defeasible logic rule program in RuleML notation [15]. The RuleML document may also contain the URI of the input RDF document on which the rule program will run,

which is forwarded to the RDF loader. The RuleML program is translated into the native DR-DEVICE rule notation using the Xalan XSLT processor [37] and an XSLT stylesheet. The DR-DEVICE rule program is then forwarded to the rule translator.

The rule translator accepts from the rule loader (or directly from the user) a set of rules in DR-DEVICE notation and translates them into a set of CLIPS production rules. The translation of the defeasible logic rules is performed in two steps: first, the defeasible logic rules are translated into sets of deductive, derived attribute and aggregate attribute rules of the basic R-DEVICE rule language (section 5.1), and then, all these rules are translated into CLIPS production rules ([10], [11]). When the translation ends, CLIPS runs the production rules and generates the objects that constitute the result of the initial rule program or query. Finally, the result-objects are exported to the user as an RDF/XML document through the RDF extractor.

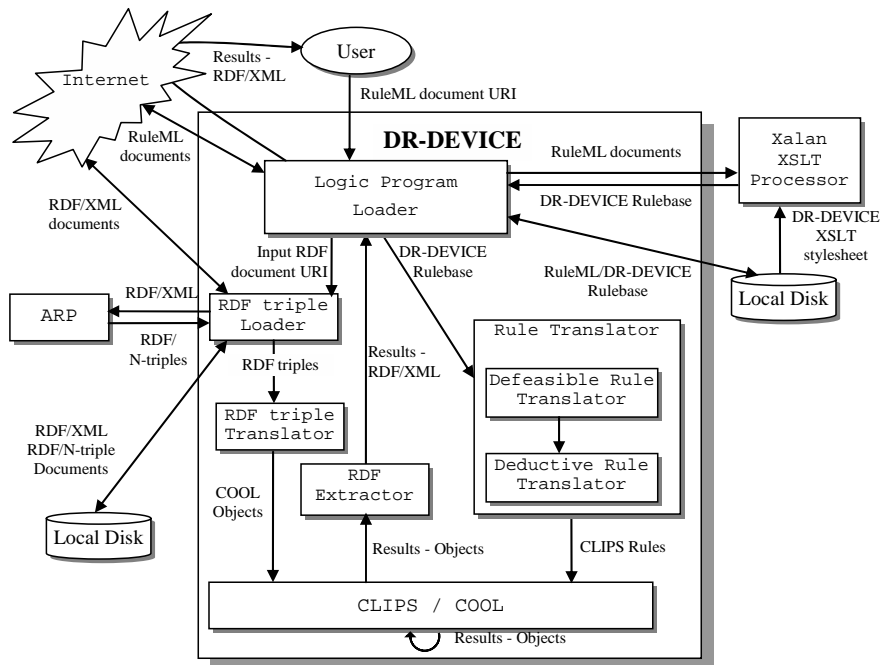


Fig. 1. Architecture of the DR-DEVICE system.

4.1 The R-DEVICE System

In this subsection we give a brief overview of the R-DEVICE system which is the basis for building DR-DEVICE. R-DEVICE ([10], [11]) is a deductive object-oriented knowledge base system, which transforms RDF triples into objects and uses a deductive rule language for querying and reasoning about them.

Triple-to-object mapping scheme

R-DEVICE imports RDF data into the CLIPS production rule system [17] as COOL objects. The main difference between the RDF data model and our object model is that we treat properties both as first-class objects and as attributes of resource objects. In this way properties of resources are not scattered across several triples as in most other RDF storage and querying systems, resulting in increased query performance due to less joins. The main features of this mapping scheme are the following:

- Resource *classes* are represented both as COOL classes and as direct or indirect instances of the `rdfs:Class` class. This binary representation is due to the fact that COOL does not support meta-classes. Class names follow the `ns:anchorID` format, while their corresponding instances have an object identifier with the same name, surrounded by square brackets.
- All *resources* are represented as COOL objects, direct or indirect instances of the `rdfs:Resource` class. The identifier of a resource object is the same as the URI address of the resource, except if their address can be abbreviated to a `ns:label`.
- Finally, *properties* are direct or indirect instances of the class `rdf:Property`. Furthermore, properties are defined as slots (attributes) of their domain class(es). The values of properties are stored inside resource objects as slot values. Actually, RDF properties are multislots, i.e. they store lists of values, because a resource can have multiple times the same property attached to it.

The descriptive semantics of RDF data may call for dynamic redefinitions of the OO schema, which are handled by R-DEVICE.

The Rule Language of R-DEVICE

R-DEVICE features a powerful deductive rule language which is able to express arbitrary queries both on the RDF schema and data, including recursion, stratified negation, ground and generalized path expressions over the objects, derived attributes and aggregate, grouping, and sorting functions, mainly due to the second-order syntax of the rule language which is efficiently translated into sets of first-order logic rules using metadata. R-DEVICE rules define views which are materialized and incrementally maintained. Finally, users can use and define functions using the CLIPS host language. R-DEVICE belongs to a family of previous such deductive object-oriented rule languages ([12], [13]). Deductive rules are implemented as CLIPS production rules and their syntax is a variation of the CLIPS syntax. Examples of rules can be found in the next section, as well as in [36].

5. The Defeasible Logic Language of DR-DEVICE

There are three types of rules in DR-DEVICE, closely reflecting defeasible logic: strict rules, defeasible rules, and defeaters. Rule type is declared with keywords `strictrule`, `defeasiblerule`, and `defeater`, respectively. For example, the following rule construct represents the defeasible rule `r4: bird(X) => flies(X)`.

```
(defeasiblerule r4
  (bird (name ?X))
  =>
```

```
(flies (name ?X))
```

Predicates have named arguments, called slots, since they represent CLIPS objects. DR-DEVICE has also a RuleML-like syntax [15]. The same rule is represented in RuleML notation (version 0.85) as follows:

```
<imp>
  <_rlab><ind type="defeasiblerule">r4</ind></_rlab>
  <_head>
    <atom>   <_opr><rel>bird</rel></_opr>
              <_slot name="name"><var>X</var></_slot>
    </atom>
  </_head>
  <_body>
    <atom>   <_opr><rel href="flies"/></_opr>
              <_slot name="name"><var>X</var></_slot>
    </atom>
  </_body>
</imp>
```

We have used the `type` attribute inside the `ind` element of the rule label (`_rlab`) to denote rule type. However, several features of defeasible logic and its DR-DEVICE implementation could not be captured by the latest RuleML DTDs, so we have developed a new DTD using the modularization scheme of RuleML, extending the Datalog with strong negation DTD.

Superiority relations are represented as attributes of the superior rule. For example, the following rule `r5` is superior to rule `r4` that has been presented above.

```
(defeasiblerule r5
  (declare (superior r4))
  (penguin (name ?X))
  =>
  (not (flies (name ?X))))
```

In RuleML notation, there is a `superiority` attribute in the rule label.

```
<imp>
  <_rlab superior="r4"><ind type="defeasiblerule">r5</ind></_rlab>
  ...
</imp>
```

Classes and objects (facts) can also be declared in DR-DEVICE; however, the focus in this paper is the use of RDF data as facts. The input RDF file(s) are declared in the `rdf_import` attribute of the `rulebase` (root) element of the RuleML document. There exist two more attributes in the `rulebase` element: the `rdf_export` attribute that declares the address of the RDF file with the results of the rule program to be exported, and the `rdf_export_classes` attribute that declares the derived classes whose instances will be exported in RDF/XML format. Further extensions to the RuleML syntax, include function calls that are used either as constraints in the rule body or as new value calculators at the rule head. Furthermore, multiple constraints in the rule body can be expressed through the logical operators: `_not`, `_and`, `_or`. Examples of all these can be found in the next section (Fig. 5, Fig. 6).

5.1 Translating Defeasible Rules

The translation of defeasible rules into R-DEVICE rules is based on the translation of defeasible theories into logic programs through a meta-program ([31]). We use the meta-program to guide defeasible rule compilation. Each *defeasible rule* in DR-DEVICE is translated into a set of 5 R-DEVICE rules:

- A *deductive* rule that generates the derived defeasible object when the condition of the defeasible rule is met.
- An aggregate attribute “*support*” rule that stores the rule ids of the rules that can potentially prove positively or negatively the object.
- A derived attribute “*overruled*” rule that stores the rule id of the rule that has overruled the positive or the negative proof of the defeasible object, if the rule condition has been at least defeasibly proven, and if the rule has not been defeated by a superior rule.
- A derived attribute “*defeasibly*” rule that defeasibly proves either positively or negatively an object, if the rule condition has been at least defeasibly proven, if the opposite conclusion has not been definitely proven and if the rule has not been overruled by another rule.
- A derived attribute “*defeated*” rule that stores the rule id of the rule that has defeated overriding rules when the former is superior to the latter, if the rule condition has been at least defeasibly proven. A “defeated” rule is generated only for rules that have a superiority relation, i.e. they are superior to others.

Strict rules are handled in the same way as defeasible rules, with an addition of a derived attribute rule (called *definitely* rule) that definitely proves either positively or negatively an object, if the condition of the strict rule has been definitely proven, and if the opposite conclusion has not been definitely proven.

Defeaters are much weaker rules that can only overrule a conclusion. Therefore, for a defeater only the “overruled” rule is created, along with a deductive rule to allow the creation of derived objects, even if their proof status cannot be supported by defeaters.

Execution Order. The order of execution of all the above rule types is as follows: “deductive”, “support”, “definitely”, “defeated”, “overruled”, “defeasibly”. Moreover, rule priority for stratified defeasible rule programs is determined by stratification. Finally, for non-stratified rule programs rule execution order is not determined. However, in order to ensure the correct result according to the defeasible logic theory for each derived attribute rule of the rule types “definitely”, “defeated”, “overruled” and “defeasibly” there is an opposite “truth maintenance” derived attribute rule that undoes (retracts) the conclusion when the condition is no longer met. In this way, even if rules are not executed in the correct order, the correct result will be eventually deduced because conclusions of rules that should have not been executed can be later undone.

DR-DEVICE has been extensively tested using a tool that generates scalable test defeasible logic theories that comes with Deimos, a query answering defeasible logic system [30].

6. Use Case of Defeasible Reasoning over RDF Data

In this section we present a full example of using DR-DEVICE rules in a brokered trade application that takes place via an independent third party, the broker. The broker matches the buyer's requirements and the sellers' capabilities, and proposes a transaction when both parties can be satisfied by the trade. In our case, the concrete application (which has been adopted from [7]) is apartment renting and the landlord takes the role of the abstract seller.

1. *Apartment Requirements*
 - Carlos is looking for an apartment of at least 45m² with at least 2 bedrooms.
 - If it is on the 3rd floor or higher, the house must have an elevator.
 - Also, pet animals must be allowed.
2. *Price Requirements*
 - Carlos is willing to pay \$300 for a centrally located 45m² apartment, and \$250 for a similar flat in the suburbs.
 - In addition, he is willing to pay an extra \$5 per m² for a larger apartment, and \$2 per m² for a garden.
 - He is unable to pay more than \$400 in total.
3. *Preferences*
 - If given the choice, he would go for the cheapest option.
 - His 2nd priority is the presence of a garden.
 - Lowest priority is additional space.

Fig. 2. Verbal description of Carlo's (a potential renter) requirements.

```
<!DOCTYPE rdf:RDF [  
  ...  
  <!ENTITY carlo "http://.../dr-device/carlo/carlo.rdf#">  
>  
<rdf:RDF  
  ...  
  xmlns:carlo="&carlo;">  
  
  <carlo:apartment rdf:about="&carlo;a1">  
    <carlo:bedrooms rdf:datatype="&xsd;integer">1</carlo:bedrooms>  
    <carlo:central>yes</carlo:central>  
    <carlo:floor rdf:datatype="&xsd;integer">1</carlo:floor>  
    <carlo:gardenSize rdf:datatype="&xsd;integer">0</carlo:gardenSize>  
    <carlo:lift>no</carlo:lift>  
    <carlo:name>a1</carlo:name>  
    <carlo:pets>yes</carlo:pets>  
    <carlo:price rdf:datatype="&xsd;integer">300</carlo:price>  
    <carlo:size rdf:datatype="&xsd;integer">50</carlo:size>  
  </carlo:apartment>  
  ...  
</rdf:RDF>
```

Fig. 3. RDF document for available apartments

Available apartments reside in an RDF document (Fig. 3). The requirements of a potential renter, called e.g. Carlo, are shown in Fig. 2. These requirements are expressed in DR-DEVICE's defeasible logic rule language as shown in Fig. 4 (in native CLIPS-like syntax). Rules `r1` and `r2` cover some of the first set of requirements in

Fig. 2, rules `r7` and `r9` represent requirements from the second set and rules `r10`, `r11` from the third. Finally, rules `cheapest1` and `cheapest2` calculate the cheapest of the acceptable apartments. The complexity of the rule `cheapest2` is due to the lack of conflicting literals support in DR-DEVICE.

```
(import-rdf "http://.../dr-device/carlo/carlo.rdf")
(export-rdf "http://.../dr-device/carlo/export-carlo.rdf" acceptable rent)
(defeasiblerule r1
  (carlo:apartment (carlo:name ?x))
  =>
  (acceptable (apartment ?x)))
(defeasiblerule r2
  (declare (superior r1))
  (carlo:apartment (carlo:name ?x) (carlo:bedrooms ?y&:(< ?y 2)))
  =>
  (not (acceptable (apartment ?x))))
...
(defeasiblerule r7
  (carlo:apartment (carlo:name ?x) (carlo:size ?y&:(>= ?y 45))
    (carlo:gardenSize ?z) (carlo:central "yes"))
  =>
  (calc (bind ?a (+ 300 (* 2 ?z) (* 5 (- ?y 45))))
    (offer (apartment ?x) (amount ?a))))
...
(defeasiblerule r9
  (declare (superior r1))
  (offer (apartment ?x) (amount ?y))
  (carlo:apartment (carlo:name ?x) (carlo:price ?z&:(< ?y ?z)))
  =>
  (not (acceptable (apartment ?x))))
(defeasiblerule cheapest1
  (acceptable (apartment ?x))
  =>
  (cheapest (apartment ?x)))
(defeasiblerule cheapest2
  (declare (superior cheapest1))
  (acceptable (apartment ?x))
  (carlo:apartment (carlo:name ?x) (carlo:price ?z))
  (acceptable (apartment ?y&~?x))
  (carlo:apartment (carlo:name ?y) (carlo:price ?w&:(< ?w ?z)))
  =>
  (not (cheapest (apartment ?x))))
...
(defeasiblerule r10
  (cheapest (apartment ?x))
  =>
  (rent (apartment ?x)))
(defeasiblerule r11
  (declare (superior r10))
  (cheapest (apartment ?x))
  (not (largestGarden (apartment ?x)))
  (cheapest (apartment ?y&~?x))
  (largestGarden (apartment ?y))
  =>
  (not (rent (apartment ?x))))
...
```

Fig. 4. Part of Carlo's requirements in native (CLIPS-like) DR-DEVICE syntax

Rules `r2` and `r7` are shown in Fig. 5 in the RuleML-like syntax of DR-DEVICE. Things to notice here is the expression of the superiority relation as an attribute of the rule label, the expression of complex constraints on the value of a slot based on functions calls and logical operators, and the calculation of the values of the slots in the

rule head, through again the use of function calls. Currently, function calls are expressed as unparsed strings, directly in CLIPS-like notation. One of our future goals is to express such function calls directly in RuleML notation, should the initiative support functions.

```

<!DOCTYPE rulebase SYSTEM "http://.../dr-device/defeasible.dtd" [
  <!ENTITY carlo "http://.../dr-device/carlo/carlo.rdf#">
  <!ENTITY carlo_rb "http://.../dr-device/carlo/carlo-rbase.ruleml#">
]>
<rulebase xmlns:carlo_rb="&carlo_rb;" xmlns:carlo="&carlo;"
  rdf_import="&carlo;" rdf_export_classes="acceptable rent"
  rdf_export="http://.../dr-device/carlo/export-carlo.rdf">
  <_rbaselab>
    <ind type="defeasible" href="&carlo_rb;">carlo-rules</ind>
  </_rbaselab>
  ...
  <imp>
    <_rlab superior="r1">
      <ind type="defeasiblerule" href="&carlo_rb;r2">r2</ind>
    </_rlab>
    <_head>
      <neg>
        <atom> <_opr><rel>acceptable</rel></_opr>
          <_slot name="apartment"><var>x</var></_slot>
        </atom>
      </neg>
    </_head>
    <_body>
      <atom> <_opr><rel href="carlo:apartment"/></_opr>
        <_slot name="carlo:name"><var>x</var></_slot>
        <_slot name="carlo:bedrooms">
          <_and>
            <var>y</var>
            <function_call>(&lt; ?y 2)</function_call>
          </_and>
        </_slot>
      </atom>
    </_body>
  </imp>
  ...
  <imp>
    <_rlab><ind type="defeasiblerule" href="&carlo_rb;r7">r7</ind></_rlab>
    <_head calculations="(bind ?a (+ 300 (* 2 ?z) (* 5 (- ?y 45))))">
      <atom> <_opr><rel>offer</rel></_opr>
        <_slot name="apartment"><var>x</var></_slot>
        <_slot name="amount"><var>a</var></_slot>
      </atom>
    </_head>
    <_body>
      <atom>
        <_opr><rel href="carlo:apartment"/></_opr>
        <_slot name="carlo:name"><var>x</var></_slot>
        <_slot name="carlo:size">
          <_and><var>y</var><function_call>(>= ?y 45)</function_call></_and>
        </_slot>
        <_slot name="carlo:gardenSize"><var>z</var></_slot>
        <_slot name="carlo:central"><ind>"yes"</ind></_slot>
      </atom>
    </_body>
  </imp>
  ...
</rulebase>

```

Fig. 5. Part of Carlo's requirements in RuleML-like DR-DEVICE syntax

After the rule document in Fig. 5 is loaded into DR-DEVICE, it is transformed into the native DR-DEVICE syntax (Fig. 4). DR-DEVICE rules are further translated into R-DEVICE rules, as presented in the previous section, which in turn are translated into CLIPS production rules. Then the RDF document(s) of Fig. 3 is loaded and transformed into CLIPS (COOL) objects. Finally, the reasoning can begin, which ends up with 3 acceptable apartments and one suggested apartment for renting, according to Carlo's requirements and the available apartments [7]. The results (i.e. objects of derived classes) are exported in an RDF file according to the specifications posed in the RuleML document (Fig. 5). Fig. 6 shows an example of the result exported for class `acceptable` (acceptable or not apartments) and class `rent` (suggestions to rent a house or not). Notice that both the positively and negatively proven (defeasibly or definitely) objects are exported. Objects that cannot be at least defeasibly proven, either negatively or positively, are not exported, although they exist inside DR-DEVICE. Furthermore, the RDF schema of the derived classes is also exported.

```

<!DOCTYPE rdf:RDF [
  ...
  <!ENTITY dr-device "http://.../dr-device/export/export-carlo.rdf#">
]>
<rdf:RDF
  ...
  xmlns:dr-device='&dr-device;'>
  <rdfs:Class rdf:about='&dr-device;DefeasibleObject' />
  <rdfs:Class rdf:about='&dr-device;acceptable'>
    <rdfs:subClassOf rdf:resource='&dr-device;DefeasibleObject' />
  </rdfs:Class>
  <rdfs:Class rdf:about='&dr-device;rent'>
    <rdfs:subClassOf rdf:resource='&dr-device;DefeasibleObject' />
  </rdfs:Class>
  <rdf:Property rdf:about='&dr-device;truthStatus'>
    <rdfs:domain rdf:resource='&dr-device;DefeasibleObject' />
    <rdfs:range rdf:resource='rdfs:Literal' />
  </rdf:Property>
  <rdf:Property rdf:about='&dr-device;apartment'>
    <rdfs:domain rdf:resource='&dr-device;acceptable' />
    <rdfs:range rdf:resource='rdfs:Literal' />
  </rdf:Property>
  <rdf:Property rdf:about='&dr-device;apartment'>
    <rdfs:domain rdf:resource='&dr-device;rent' />
    <rdfs:range rdf:resource='rdfs:Literal' />
  </rdf:Property>
  ...
  <dr-device:acceptable rdf:about="&dr-device;acceptable2">
    <dr-device:apartment>a2</dr-device:apartment>
    <dr-device:truthStatus>defeasibly-not-proven</dr-device:truthStatus>
  </dr-device:acceptable>
  ...
  <dr-device:acceptable rdf:about="&dr-device;acceptable5">
    <dr-device:apartment>a5</dr-device:apartment>
    <dr-device:truthStatus>defeasibly-proven</dr-device:truthStatus>
  </dr-device:acceptable>
  ...
  <dr-device:rent rdf:about="&dr-device;rent1">
    <dr-device:apartment>a5</dr-device:apartment>
    <dr-device:truthStatus>defeasibly-proven</dr-device:truthStatus>
  </dr-device:rent>
  ...
</rdf:RDF>

```

Fig. 6. Results of defeasible reasoning exported as an RDF document

7. Related Work

There exist several previous implementations of defeasible logics. In [19] the historically first implementation, D-Prolog, a Prolog-based implementation is given. It was not declarative in certain aspects (because it did not use a declarative semantic for the not operator), therefore it did not correspond fully to the abstract definition of the logic. Finally it did not provide any means of integration with Semantic Web layers and concepts.

Deimos [30] is a flexible, query processing system based on Haskell. It does not integrate with Semantic Web (for example, there is no way to treat RDF data; nor does it use an XML-based or RDF-based syntax). Thus it is an isolated solution.

Delores [30] is another implementation, which computes all conclusions from a defeasible theory (the only system of its kind known to us). It is very efficient, exhibiting linear computational complexity. However, it does not integrate with other Semantic Web languages and systems.

Another Prolog-based implementation of defeasible logics is in [3], which places emphasis on completeness (covering full defeasible logic) and flexibility (covering all important variants). However, at present it lacks the ability of processing RDF data.

SweetJess [25] is another implementation of a defeasible reasoning system (situated courteous logic programs) based on Jess. It integrates well with RuleML. However, SweetJess rules can only express reasoning over ontologies expressed in DAMLRuleML (a DAML-OIL like syntax of RuleML) and not on arbitrary RDF data, like DR-DEVICE. Furthermore, SweetJess is restricted to simple terms (variables and atoms). This applies to DR-DEVICE to a large extent. However, the basic R-DEVICE language [10] can support a limited form of functions in the following sense: (a) path expressions are allowed in the rule condition, which can be seen as complex functions, where allowed function names are object referencing slots; (b) aggregate and sorting functions are allowed in the conclusion of aggregate rules. Finally, DR-DEVICE can also support conclusions in non-stratified rule programs due to the presence of truth-maintenance rules (section 5.1).

8. Conclusions and Future Work

In this paper we described reasons why conflicts among rules arise naturally on the Semantic Web. To address this problem, we proposed to use defeasible reasoning which is known from the area of knowledge representation. And we reported on the implementation of a system for defeasible reasoning on the Web. It is based on CLIPS production rules, and supports RuleML syntax.

Planned future work includes:

- Adding arithmetic capabilities to the rule language and using appropriate constraint solvers in conjunction with logic programs.
- Implementing load/upload functionality in conjunction with an RDF repository, such as RDF Suite [1] and Sesame [16].

- Study in more detail integration of defeasible reasoning with description logic based ontologies. Starting point of this investigation will be the Horn definable part of OWL [26].
- Applications of defeasible reasoning and the developed implementation for brokering, bargaining, automated agent negotiation, and personalization.

9. References

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