Chapter 1
Hybrid Reasoning with Rules and Ontologies

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Abstract. The purpose of this chapter is to report on work that has been done in the REWERSE project concerning hybrid reasoning with rules and ontologies. Two major streams of work have been pursued within REWERSE. They start from the predominant semantics of non-monotonic rules in logic programming. The one stream was an extension of non-monotonic logic programs under answer set semantics, with query interfaces to external knowledge sources. The other stream, in the spirit of the AL-log approach of enhanced deductive databases, was an extension of Datalog (with the well-founded semantics, which is predominant in the database area). The former stream led to so-called non-monotonic dl-programs and hex-programs, and the latter stream to hybrid well-founded semantics. Further variants and derivations of the formalisms (like a well-founded semantics for dl-programs, respecting probabilistic knowledge, priorities, etc.) have been conceived.

1.1 Introduction

The purpose of this chapter is to report on the work that has been done in REWERSE on hybrid reasoning with rules and ontologies. The importance of rules and ontologies for Web applications is reflected by the World Wide Web Consortium’s\(^1\) (W3C) proposal of the layered architecture of the Semantic Web, including the ontology layer and the rule layer. The ontology layer of the Semantic Web was quite developed already at the REWERSE start in 2004. In the same year, W3C adopted the Web Ontology Language (OWL) recommendation\(^32\). On the other hand, the rule layer was a topic addressed by many researchers but was not yet official subject of W3C activities.

\(^1\) http://www.w3.org/
Integration of the rule layer with the ontology layer is necessary for rule-based applications using ontologies, like data integration applications. It can be achieved by combining existing ontology languages with existing rule languages, or by defining new languages, expressive enough to define ontologies, rules and their interaction. An important issue in combination of ontology languages and rule languages based on logics is the semantics of the combined language, as a foundation for development of sound reasoners. The REWERSE work reported in this chapter focused on hybrid reasoning, where the reasoner of the combined language reuses the existing reasoners of the component ontology language and rule language.

Motivated by the need for hybrid reasoning with rules and ontologies, two major streams of work have been pursued within REWERSE. They start from the predominant semantics of non-monotonic rules in logic programming. The one stream was an extension of non-monotonic logic programs under answer set semantics, with query interfaces to external knowledge sources. The other stream, in the spirit of the $\mathcal{AL}$-log approach of enhanced deductive databases, was an extension of Datalog (with the well-founded semantics, which is predominant in the database area). The former stream lead to so-called non-monotonic dl-programs and $\text{hex}$-programs, and the latter stream to hybrid well-founded semantics. Further variants and derivations of the formalisms (like a well-founded semantics for dl-programs, respecting probabilistic knowledge, priorities, etc.) have been conceived.

To put the REWERSE work in a broader perspective, the chapter begins with a concise introduction to the Resource Description Framework (RDF) layer, which sets the standard for the data model for the Semantic Web, to the RDF Schema, seen as a simple ontology language, and to OWL. We then discuss rule languages considered in integration proposals and present a classification of the major approaches to integration which uses the terminology of [4,81]. The remaining part of the chapter surveys the REWERSE work on hybrid integration of rules and ontologies.

### 1.2 Overview of Approaches

This section gives a brief survey of the approaches to combine or integrate reasoning with rules and ontologies on the Web. It starts with a brief introduction to the underlying formalisms of the Semantic Web, followed by discussion on the rule languages considered in integration proposals. Finally, a classification of the integration proposals is presented. For a more comprehensive survey, the interested reader is referred to [40].

#### 1.2.1 RDF and RDF Schema

The Resource Description Framework (RDF) defines the data model for the Semantic Web as labeled, directed graphs. An RDF dataset (that is, an RDF graph) can be viewed as a set of the edges of such a graph, commonly represented by triples (or statements) of the form: