Chapter 2
Knowledge Representation and Reasoning in Norm-Parameterized Fuzzy Description Logics

Jidi Zhao, Harold Boley

Abstract The Semantic Web is an evolving extension of the World Wide Web in which the semantics of the available information are formally described, making it more machine-interpretable. The current W3C standard for Semantic Web ontology languages, OWL, is based on the knowledge representation formalism of Description Logics (DLs). Although standard DLs provide considerable expressive power, they cannot express various kinds of imprecise or vague knowledge and thus cannot deal with uncertainty, an intrinsic feature of the real world and our knowledge. To overcome this deficiency, this chapter extends a standard Description Logic to a family of norm-parameterized Fuzzy Description Logics. The syntax to represent uncertain knowledge and the semantics to interpret fuzzy concept descriptions and knowledge bases are addressed in detail. The chapter then focuses on a procedure for reasoning with knowledge bases in the proposed Fuzzy Description Logics. Finally, we prove the soundness, completeness, and termination of the reasoning procedure.

2.1 Introduction

The Semantic Web is an evolving extension of the World Wide Web in which the semantics of the available information are formally described by logic-based standards and technologies, making it possible for machines to understand the information on the Web [3].

Uncertainty is an intrinsic feature of real-world knowledge, which is also reflected in the World Wide Web and the Semantic Web. Many concepts needed in
knowledge modeling lack well-defined boundaries or, precisely defined criteria. Examples are the concepts of young, tall, and cold. The Uncertainty Reasoning for the World Wide Web (URW3) Incubator Group defined the challenge of representing and reasoning with uncertain information on the Web. According to the latest URW3 draft report, uncertainty is a term intended to encompass different forms of uncertain knowledge, including incompleteness, inconclusiveness, vagueness, ambiguity, and others [18]. The need to model and reason with uncertainty has been found in many different Semantic Web contexts, such as matchmaking in Web services [20], classification of genes in bioinformatics [28], multimedia annotation [27], and ontology learning [6]. Therefore, a key research direction in the Semantic Web is to handle uncertainty.

The current W3C standard for Semantic Web ontology languages, OWL Web Ontology Language, is designed for use by applications that need to process the content of information instead of just presenting information to humans [21, 23]. It facilitates greater machine interpretability of Web content than that supported by other Web languages such as XML, RDF, and RDF Schema (RDFS). This ability of OWL is enabled by its underlying knowledge representation formalism Description Logics (DLs). Description Logics (DLs) [2][1][12] are a family of logic-based knowledge representation formalisms designed to represent and reason about the conceptual knowledge of arbitrary domains. Elementary descriptions of DL are atomic concepts (classes) and atomic roles (properties or relations). Complex concept descriptions and role descriptions can be built from elementary descriptions according to construction rules. Different Description Logics are distinguished by the kinds of concept and role constructors allowed in the Description Logic and the kinds of axioms allowed in the terminology box (TBox). The basic propositionally closed DL is $\mathcal{ALC}$ in which the letters $\mathcal{A}$ stand for attributive language and the letter $\mathcal{C}$ for complement (negation of arbitrary concepts). Besides $\mathcal{ALC}$, other letters are used to indicate various DL extensions. More precisely, $\mathcal{S}$ is often used for $\mathcal{ALC}$ extended with transitive roles ($R^+$), $\mathcal{H}$ for role hierarchies, $\mathcal{O}$ for nominals, $\mathcal{I}$ for inverse roles, $\mathcal{N}$ for number restrictions, $\mathcal{Q}$ for qualified number restrictions, and $\mathcal{F}$ for functional properties. OWL\footnote{In the following, OWL refers to OWL 1. Similar sublanguages exist for OWL 2.} has three increasingly expressive sublanguages: OWL Lite, OWL DL, and OWL Full. If we omit the annotation properties of OWL, the OWL-Lite sublanguage is a syntactic variant of the Description Logic $\mathcal{SHIF}(D)$ where $(D)$ means data values or data types, while OWL-DL is almost equivalent to the $\mathcal{SHOIN}(D)$ DL [13]. OWL-Full is the union of OWL syntax and RDF, and known to be undecidable mainly because it does not impose restrictions on the use of transitive properties. Accordingly, an OWL-Lite ontology corresponds to a $\mathcal{SHIF}(D)$ knowledge base, and an OWL-DL ontology corresponds to a $\mathcal{SHOIN}(D)$ knowledge base.

Although standard DLs provide considerable expressive power, they are limited to dealing with crisp, well-defined concepts and roles, and cannot express vague or uncertain knowledge. To overcome this deficiency, considerable work has been carried out in integrating uncertain knowledge into DLs in the last decade. One im-