# Context Representation and Reasoning with Formal Ontologies

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**Abstract**

Ontologies are not only becoming a widespread formalism to create the knowledge base of current intelligent and semantic systems, but they are also suitable for modeling context information in ubiquitous applications, which require expressive representation and reasoning languages. In this paper, we discuss different approaches for ontological context management, as well as a proposal to represent and exploit significance-based relations with standard and fuzzy ontologies.

## 1. Introduction

Next-generation pervasive and ubiquitous applications are expected to provide users with services tailored to their needs anytime and anywhere. The Knowledge Mobilization approach envisions future computing systems that are: *ubiquitous* –accessible and mobile–, *proactive* –able to discover what service is convenient–, *declarative* –users do not have to specify how to retrieve information, only what is needed–, *integrative* –heterogeneous sources, technologies and devices are involved–, and *concise* –users are not overwhelmed with irrelevant data (Gómez-Romero 2008). The cornerstone of Knowledge Mobilization is context knowledge, which must be retrieved, processed and applied to adapt system behavior automatically according to a priori preferences, past situations, ongoing activities and the current scenario.

In the area of Ubiquitous Computing, context is any information (implicit or explicit) that can be used to characterize the situation of an entity (Dey and Abowd 2000). More specifically, context is usually considered a mix of geo-spatial data, ambient sensor inputs, user profiles (preferences, intentions, history, etc.), and service descriptions (Schmidt, Beigl and Gellersen 1999). Several proposals in the literature have only taken into account *ad hoc* context representations mostly based on application-dependent heuristics. The main drawback of these approaches is that they are hardly applicable to different domains, difficult to scale, and costly to integrate with other systems. In contrast, cognitive approaches propose to build a symbolic model of the world (either context or domain-specific knowledge), usually expressed in a logic-based language. Cognitive approaches are more extensible, but they also require the implementation of suitable knowledge acquisition methodologies and tools, representation formalisms, and reasoning procedures.

Ontologies have received considerable interest in the last decade as suitable conceptual models for context management. An ontology is a representation of the mereological aspects of a reality created from a common perspective and expressed in a formal language (Gruber 1993), such as the current standard Web Ontology Language (OWL 2) (Hitzler et al. 2009). The basic ontological representation primitives are concepts, relations, instances and axioms. Reasoning with ontologies is an automatic procedure that obtains new axioms that have not been explicitly included in the knowledge base, but are logical consequences of the represented axioms. Ontologies offer two remarkable advantages in context management: (i) ontologies have strong underpinnings in Description Logics (DLs), which are very well-known computable formalisms for structured knowledge representation and reasoning; (ii) ontologies promote knowledge exchange and reusability, since they are supported by standard languages and can be easily specialized or extended in specific applications.

Ontologies are the knowledge representation formalism proposed for the Semantic Web. The Semantic Web is an extension of the current Web, whose aim is the automation of document processing and information retrieval by giving information "a well-defined meaning, better enabling computers and people to work in cooperation" (Berners-

Lee, Hendler and Lassila 2001). The meaning of web resources is represented by means of formal metadata expressed in an ontology language (e.g., OWL 2). Not surprisingly, the Semantic Web is contributing to the advancement of ontology theory, methodologies and supporting tools, which can be surely exploited in pervasive applications. In addition, the development of the *Internet of Things* paradigm, which assumes that every common-use device is connected to the Internet, makes it clear that synergistic approaches are likely to succeed in the near future.

Nevertheless, despite the advantages of ontologies, it has been widely pointed out that they are not appropriate to deal with uncertain, imprecise and vague information, which is inherent to several real world domains (Sanchez 2006). In particular, this problem arises with context knowledge: sensor data may be imprecise; activity recognition procedures may be uncertain; information integration may be only partially trusted; etc. Fuzzy set theory and fuzzy logic have proved to be suitable formalisms to handle these types of knowledge. Therefore several fuzzy extensions of DLs, thus yielding fuzzy ontologies, can be found in the literature (Lukasiewicz and Straccia 2008). Fuzzy ontologies allow the representation of imprecise contexts, which can be used to obtain an approximate matching of the current scenario with pre-defined situations, as well as to rank the relevance of available information and services to the inferred context. Fuzzy ontologies have not achieved the maturity of crisp ontologies, and additional research should be carried out on this topic.

In previous research works, we proposed a solution to avoid information overload in Knowledge Mobilization systems: a design pattern to develop ontologies that explicitly represent relevance relations between domain-specific information and users' context. We presented two formulations of the *CDS* (Context-Domain Significance) pattern: (i) a first specification for the creation of fully OWL compliant contextualized ontologies (Bobillo, Delgado and Gómez-Romero 2008a); (ii) a fuzzy extension that supports result ranking (Bobillo, Delgado and Gómez-Romero 2008b). In addition, we described suitable reasoning mechanisms in each case to infer the domain information which is significant to a given context, and offered supporting tools to manage these ontologies. These results have been recently applied to the problem of contextual object tracking and scene interpretation from video data (Gómez-Romero et al. 2011). In that paper, we proposed a framework aimed at the construction of a symbolic model of the perceived scene (in terms of objects and activities). We have also studied fuzzy ontologies from a formal perspective, which has resulted in the creation of various extensions to crisp DLs (Bobillo, Delgado and Gómez-Romero 2009; Bobillo et al. 2009), and the development of DELOREAN, the first reasoning engine that supports fuzzy extensions of OWL 2.

This paper is aimed to provide a general overview of the state of the art in ontology-based context management researches (section 2), while encouraging discussions about prospective directions for future work (section 5). We provide a brief description of the CDS pattern (sections 3 and 4), which may be useful as a starting point for the development of standardized means for the representation of context-dependent significance.

## 2. Related Work

Current approaches to ontology-based context knowledge exploitation can be classified into three main areas. Ranging from the most theoretical to the most practical, they are: contextualization of ontologies, ontology design patterns, and ontology-based context-aware systems.

### Contextualization of Ontologies

There is a large literature on contextualization of ontologies which analyzes how external or additional knowledge influences the interpretation of an ontology in terms of consistency, validity, partitioning, etc. Contextualization is mainly concerned with non-monotonic models, since it involves reasoning with models which are satisfiable or not depending on the available knowledge (Minker 1993). The open world assumption usually stands in DL reasoning, which makes ontologies a monotonic formalism (Bossu and Siegel 1985). Some extensions proposed to allow non-monotonicy in DLs are: epistemic queries, default reasoning, circumscription, belief revision, and hybridization with Logic Programming. As a matter of fact, additional primitives have been proposed to endow the OWL language with contextualization features. Context and micro-theories have been studied to allow OWL to solve context-dependent aggregation problems in the Semantic Web (Guha, McCool and Fikes 2004). C-OWL is another extension to define mappings (via bridge rules) between locally-interpreted and globally-valid ontologies (Bouquet et al. 2004). Additional approaches are described in (Haase et al. 2006): ε-connections, Bayesian networks, probabilistic and possibilistic logics, multi-viewpoint reasoning and context-based selection functions.

### Ontology Design Patterns

Ontology design patterns are defined as recipes to help ontology developers to capture aspects of the application domain and represent them with existing languages from a common and well-understood perspective. Design patterns describe recurrent modeling scenarios and provide guidelines for correctly incorporating this knowledge into an ontology (Svátek 2004). The task force Ontology Engineering and Patterns was created inside the W3C Semantic Web Best Practices and Deployment Working Group in order to elaborate guidelines and design patterns for OWL.

General ontology design patterns can be found in the literature, such as the language-independent patterns proposed by (Staab, Erdmann and Maedche 2001). Other research studies focus on the ontology development process and the role of patterns during the ontology lifecycle. For example, in (Gangemi 2005), CODePs (Conceptual Ontology Design Patterns) are described. Besides, there is a growing interest in the automatic discovery and application of design (Blomqvist 2007). Unfortunately, to the best of our knowledge, there is no specific pattern aimed to the representation of context knowledge, either for specific or general domains – with the exception of the CDS pattern.

### Context-Aware Systems

Context-aware computing entails two activities: (i) interpreting the current user situation; (ii) using contextual knowledge to improve the performance of the system. As mentioned, ontologies are being intensively used to represent and reason about users' activities, and to prune available knowledge to suit to their needs. Authors agree that the combination of different technologies (Multi-Agent Systems, Semantic Web, Mobile Computing) will play a key role in the implementation of smart context-aware systems –e.g., (Lassila and Khushraj 2005). There are several applied works presenting practical implementations of context-aware frameworks and systems. Gaia is a middleware for mobile applications that relies on ontologies for the description of context predicates (Ranganathan and Campbell 2003). In this platform, components are modeled as agents; they are communicated with CORBA; and their context is represented with DAML+OIL (a predecessor of OWL). Gaia has been extended to incorporate fuzzy, probabilistic and Bayesian formalisms to process uncertain facts about general context data (Ranganathan, Al-Muhtadi and Campbell 2004). SOCAM (Service-Oriented Context-Aware Middleware) follows a similar approach to Gaia, but it is based on OWL and a service-oriented architecture (Gu, Pung and Zhang 2005). The OWL Services Framework (OWL-SF), in turn, proposes a REST architecture and a supporting framework based on OWL for context representation and reasoning, and OMG Super Distributed Objects for sensor management (Mrohs 2005). CoBrA (Context Broker Architecture) is another infrastructure which also represents context using a RDF/OWL model (Chen et al. 2004) based on the SOUPA ontology (Chen, Finin and Joshi, 2005). It is also interesting to mention the work by (Anagnostopoulos, Ntarladimas and Hadjiefthymiades 2007), who presented a fuzzy methodology to measure partial equivalences between situations (expressed using OWL ontologies) and to determine suitable action rules to be fired in pervasive applications.

## 3. Context Management with Standard Ontologies: Context-Domain Significance

The CDS design pattern is a new proposal to represent significance relations depending on context in ontology-based systems. The CDS pattern defines a blueprint to develop a new OWL ontology –namely, the significance or CDS ontology. This ontology explicitly relates context descriptions, created with a context ontology, with domain-specific expressions, which represent knowledge specific of the application domain. Given a CDS ontology, it is possible to infer which domain knowledge ought to be considered in a given situation by performing ontological reasoning.

*Example*: Electronic health records summarization

Let us assume the following example scenario. We have a physicist who wants to prescribe a treatment for a patient. To avoid side effects, the hospital information system should provide a brief report of the patient's clinical history including only information relevant to the patient's state, the diagnosis and clinical procedure that is being carried out. For example, if the patient is unconscious and has a hemorrhagic laceration, information regarding whether he has an allergy to procaine (an anesthetic drug which reduces bleeding but is also often badly metabolized and triggers allergic reactions) should be taken into account, among other things.

A CDS ontology is built from two basic subontologies, one representing domain-specific knowledge (the domain ontology) and another defining a vocabulary to describe context situations (the context ontology). In our example, the domain ontology represents which clinical records are available: procaine intolerance, penicillin intolerance, coagulation disorders, blood pressure disorders, etc. The context ontology contains terms to describe the clinical situation of a patient: unconsciousness, wound existence and situation, etc. Essentially, the CDS ontology is a new ontology that includes specific concepts (named σ-connections) connecting a complex concept $C_i$ (defined with elements of the context ontology) and a complex concept $D_j$ (defined with elements of the domain ontology). A σ-connection $P_{i,j}$ between $C_i$ and $D_j$ states that $D_j$ is relevant in situation $C_i$. The σ-connection is asserted through two specific properties $R_c$ and $R_d$ that link $P_{i,j}$ with $C_i$ and $D_j$, respectively. Notice that the context and the domain ontologies can be built by extending and reusing previous or external knowledge sources; e.g., the publicly-available medical ontology Galen (Rogers et al 2001), in our example. The formal specification of the CDS pattern and the properties of the resulting ontology are discussed in (Bobillo, Delgado and Gómez-Romero 2008a).

*Example*: Context, domain and CDS ontologies

*Domain ontology*
DrugIntollerance **isA**
  HealthDataRegister
ProcaineIntollerance **isA**
  DrugIntollerance

*Context ontology*
Unconsciousness **isA**
  galen:DisorderOfConsciousness
Hemorrhage **equivalentTo**
  galen:HaemorrhagingProcess
IrregularPenetrationWound **equivalentTo**
  galen:laceration
IrregularPenetrationWound **isA**
  PenetrationWound

*CDS ontology*
$C_0$ **equivalentTo**
  Unconsciousness **and**
  Hemorrhage **and**
  IrregularPenetrationWound
$D_0$ **equivalentTo**
  DrugIntollerance
$P_{0,0}$ **equivalentTo**
  (hasClinicalFact **some** $C_0$) **and**
  (hasElectronicRegister **some** $D_0$)

The main reasoning task involving a significance ontology consists in finding all the concepts in the domain ontology which ought to be considered in a given context. This task can be performed by carrying out a complete and decidable ontological inference procedure. The output of this process is the set of simple concepts included in the domain ontology associated to the input query context; i.e., the restricted domain.

*Example*: Retrieval of significant domain information

Let us assume the previous definitions of the context, domain and CDS ontologies. Which information of the hospital information system should be checked if the doctor is treating a hemorrhagic and unconscious patient with a penetration wound? In this case, the input context is:

E **equivalentTo**
  Hemorrhage **and**
  Unconsciousness **and**
  PenetrationWound

The restricted domain of E is:

I **= {** DrugIntollerance**,**
  ProcaineIntollerance **}**

The computational complexity of the reasoning process to retrieve context-significant domain knowledge is mainly conditioned by the complexity of $C_i$ and $D_j$ expressions, since the definitions of $P_{i,j}$ concepts are circumscribed (at most) to the basic Description Logic $\mathcal{ALC}$. If $C_i$ and $D_j$ do not involve more expressive primitives than existential qualification, the complexity of reasoning with the CDS ontology is EXPTIME-complete.

## 4. Fuzzy Context Definition and Retrieval

The significance ontology resulting from applying the CDS pattern has two main drawbacks. Firstly, definitions of complex context concepts $C_i$ (respectively for definitions of complex domain concepts $D_j$) are crisp. Consequently, it is not possible to directly represent vague contexts, e.g. "the patient is slightly unconscious", and partial similarity between contexts, e.g. "anaphylaxis is quite similar to sepsis". The second problem is that even though the significance ontology allows asserting which domain-specific knowledge is interesting in a scenario, it does not measure how important this connection is, which is desirable. For instance, in our example, some electronic registers about previous adverse drug events are more important than others, and should be firstly presented to the doctor; e.g., avoiding an anaphylactic shock is a major priority in healthcare. Ranking the significance relations would allow system responses to be sorted by precedence and setting a threshold in order to retrieve only the top $k$ most relevant concepts of the domain ontology.

We proposed an extension of the CDS design pattern to: (i) represent vague context and domain concepts; (ii) quantify the importance of σ-connections (Bobillo, Delgado and Gómez-Romero 2008b). This extension relies on fuzzy Description Logics (fuzzy DLs), a logic formalism which combines Fuzzy Logic theory and Description Logics to define a sound framework to represent and reason with imprecise and vague knowledge in ontologies.

Briefly, fuzzy DLs extend DLs by allowing concepts to denote fuzzy sets of individuals, and roles to denote fuzzy binary relations, in such a way that: (i) and individual may belong to a concept to a certain degree in [0, 1]; (ii) a pair of individuals of the domain may belong to a role in a certain degree in [0, 1]. Axioms are also extended to the fuzzy case and may hold to a degree; for example, given two fuzzy concepts, a fuzzy subsumption axiom defines a fuzzy inclusion relation between them. Fuzzy DLs require the development of new reasoning algorithms and tools, since crisp procedures (like tableau-based algorithms) are not valid. This is the approach of the experimental reasoner fuzzyDL (Bobillo and Straccia 2008), which implement an specific algorithm to reason with fuzzy ontologies. An alternative solution is to define reduction procedures to transform a fuzzy knowledge base into a crisp knowledge base while preserving the semantics of the representation, which allows using existing inference engines (Bobillo, Delgado and Gómez-Romero 2009).

The fuzzy *fCDS* ontology extends the original proposal by allowing contexts, domains, and σ-connections to be defined by means of fuzzy subsumption axioms. Thus, context descriptions can be partially similar, as well as domain concepts. In addition, the degree of subsumption in a σ-connection represents the importance value of the link between the context and the domain. Accordingly, the fCDS ontology contains definitions for $C_i$, $D_j$ and $P_{i,j}$ created with fuzzy concept inclusion axioms. In our example, a fuzzy $C_i$ denotes an imprecise definition of a patient situation, whereas $D_j$ have crisp semantics. For instance, we are representing that anaphylaxis is similar to shock with degree 0.7.

*Example*: Fuzzy context, domain and CDS ontologies

*Extensions to the context ontology*
Elderly **isA**$_{>=1}$
  hasAge **some** trapezoid{60,75,120,120}
Anaphylaxis **isA**$_{>=0.7}$
  Shock
SepticShock **isA**$_{>=0.5}$
  Anaphylaxis
Shock **and** hasComplication >= 1 Thing **isA**$_{>=0.8}$
  EpinephrineAdmin

*Extensions to the CDS ontology*
$C_1$ **isA**$_{>=1}$
  hasComplication **some** Elderly
$C_2$ **isA**$_{>=1}$
  Anaphylaxis
$C_3$ **isA**$_{>=1}$
  EpinephrineAdmin
$D_1$ **isA**$_{>=1}$
  CurrentPrescription
$D_2$ **isA**$_{>=1}$
  CurrentPrescription **or**
  DrugIntollerance
$D_3$ **isA**$_{>=1}$
  Antidepressive
$D_3$ **isA**$_{>=1}$
  $D_1$
$P_{1,1}$ **isA**$_{>=0.6}$
  (hasClinicalFact **some** $C_1$) **and**
  (hasElectronicRegister **some** $D_1$)
$P_{2,2}$ **isA**$_{>=0.5}$
  (hasClinicalFact **some** $C_2$) **and**
  (hasElectronicRegister **some** $D_2$)
$P_{3,3}$ **isA**$_{>=0.9}$
  (hasClinicalFact **some** $C_3$) **and**
  (hasElectronicRegister **some** $D_3$)

An extension of the crisp reasoning algorithm has been developed to retrieve the concepts of the domain-ontology that are relevant in a given fuzzy context and the degree of interest. The degree of interest is computed on the inclusion values defined in the subsumption axioms included the CDS ontology. Since the same domain concept may be retrieved with more than a degree through different profiles, the obtained values are aggregated using a t-conorm.

*Example*: Fuzzy retrieval of significant domain information

Let us assume the previous definitions of the context, domain and CDS ontologies and the query context below:

E **equivalentTo**
  Anaphylaxis **and**
  (hasComplication **some** (hasAge **some** 80))

The restricted domain of E after aggregation is shown below. Gödel t-norm (min), t-conorm (max) and implication are used):

I **= {**
  | CurrentPrescription, 0.7 |,
  | DrugIntollerance, 0.7 |,
  | Antidepressives, 0.7 | **}**

The main problem of the reasoning algorithm is that it has a high upper-bound computational complexity. Besides, the complexity of the reduction to a crisp ontology must be considered if a specific fuzzy DL reasoner is not used. Therefore, the overhead produced by the fuzzy extension is recommended only in applications that require very high descriptive context languages.

## 5. Conclusions and Future Work

There are several prospective directions for future work in ontology-based context management that should be explored. The most important one is that current developments are still far from for widespread use. It would be convenient to face real-world problems and study their applicability, in order to establish a common development framework, encompassing standard languages and supporting tools. This effort is especially required in the topic of fuzzy ontologies. In addition, specific aspects of representations, such as temporal and spatial knowledge, must be also tackled. Moreover, context representation and reasoning formalisms must be more extensively studied in close cooperation with context acquisition and activity recognition tasks, which may determine the nature of the representation and the aim of the reasoning processes. The eventual objective of this research is the proposal of a standard to represent significance relations in ontologies with high expressive power and low computational requirements.

## Acknowledgments

This research activity is supported in part by projects CAM CONTEXTS (S2009/TIC-1485) and P07-TIC-02786.


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