Context Representation for the Semantic Web

Jie Bao, Jiao Tao, Deborah L. McGuinness
Tetherless World Constellation
Rensselaer Polytechnic Institue
Troy, NY 12180
{baojie,taoj2,dlm}@cs.rpi.edu

Paul R. Smart
School of Electronics and Computer Science
University of Southampton
Southampton, SO17 1BJ, UK
ps02v@ecs.soton.ac.uk

ABSTRACT

Context modeling is critical for the unambiguous and effective delivery of data and knowledge on the Web, and in particular, the Semantic Web. However, Contexts are often embedded in the application programs or are implied by the application- or community-specific agreements. In this paper, we propose a framework for contexts modeling that can provide formal and explicit representations for contexts on the Semantic Web. The core component of the framework is a new formalism of contexts based on the notion of jurisdictions of knowledge statements. We also discuss the semantic assumption (modeled as institutions) and provenance aspects of contexts.

1. INTRODUCTION

The unambiguous and effective delivery of data and knowledge on the Web relies heavily on the correct representation and understanding of the associated contexts. However, the current way of encoding contexts of data and knowledge on the Web is largely ad hoc. Contexts are often embedded in the application programs or are implied by the application- or community-specific agreements. This makes the linking and reusing of data and knowledge, and thus the integration of Web applications, a difficult problem. Therefore, building the architectural support for contexts is one of the major challenges for the Web, and in particular, for the Semantic Web [31].

While the research of contexts has been extensively discussed in AI (see [2] for a survey), there are still no comprehensive studies on the generic and formal representation for contexts on the Semantic Web. Notable exceptions include C-OWL [12] and a context model for RDF [45]. However, these work only cover specific aspects of contexts, for example, C-OWL addresses only contextual ontology mappings.

In this paper we present a formalism about representing contexts on the Web by extending McCarthy's seminal work on context formalization [37] (later extended by [38]). Our main contributions are as following:

- McCarthy's context theory relates a proposition to its context using the ist ("is true") relation. However, this approach may cause problems when applied to an open system like Web since the truth of a proposition is often not applicable or unknown in a context. Our framework, instead, uses a more generic *jurisdiction* relation isin ("is in"). Thus, $\mathsf{isin}(c, p)$ means that a proposition p should be interpreted in the context c (while p is not necessarily true in c). A set of context statements (as a generalized form of "lifting axioms" in [38]) can be used to state the relations between contexts, thus supporting automated reasoning about contexts.
- While [38] does not consider semantic assumptions (e.g., the Open World Assumption) in contexts, our framework allows such assumptions to be explicitly stated as institutions [27], hence effectively avoids the risk of reusing knowledge outside of situations with its intended assumptions.
- In [38], a context is an object without a provenance description (when, where, who, etc.). Utilizing recent advances on provenance representation (e.g., PML [22, 39]), our framework allows associating a provenance model to a context.

In summary, the proposed framework for contexts provides formal and explicit representations for the usually implicit contextual assumptions of data and knowledge on the Web. This is done by supporting the description of logic institutions, relations of contexts, and provenance. Our framework is able to tackle some critical issues for extending Web as a "Social Machine" [31], such as, permitting different views on the same data, faithful knowledge integration and situation awareness.

This paper is organized as follows: In Section 2 we introduce the notion of jurisdiction-based contexts and relations between contexts (e.g., compatibility and incompatibility). In Section 3 we discuss how to represent provenance information of a context and use it in inference with the context. In Section 4 we present how to use the institution theory to formally and explicitly capture semantic assumptions used in a context, and practical approaches to make machine-readable specifications of institutions. Section 5 gives related work in AI and Semantic Web research and Section 6 concludes the paper with future work.

2. FORMALIZING CONTEXTS

In this section we introduce a formal representation of contexts, extending the McCarthy's context formalization [38] (referred as *McCarthy-style contexts* thereafter).

2.1 Contexts as Jurisdictions

One key notion in [38] is that contexts are modeled as *first class objects*. A basic relation between a proposition and a context in [38] is

$$\mathsf{ist}(c, p)$$

meaning that the proposition p *is true* in the context c.

Lifting axioms can be used to connect contexts. For example, to transfer truth from one context c_1 to a more general outer context c_2, we may use a lifting axiom:

$$\mathsf{ist}(c_1, p) \rightarrow \mathsf{ist}(c_2, p)$$

However, when applied to an open system such as the Web, the McCarthy-style context modeling often can't rightly capture the context of a proposition (often modeled as a knowledge statement in an ontology on the Semantic Web)[1]. Some typical scenarios include the following:

- *The truth value of a statement cannot be meaningfully determined in a context since it is not applicable in that context.* For example, the statement "Eric Cartman lives in South Park"[2] is true in the context of the television series "South Park", but it is meaningless to assert whether this is true or false in other contexts, for example, the context of "The Simpsons" or the context of the real world.

- *The truth value of a statement is unknown in the context where it is stated or queried against.* This may be because determining the truth value of the statement itself is an open problem (e.g., whether P=NP in the theoretical computer science), or because of the open nature of the system (e.g., even if there is no real person named "Eric Cartman" currently listed on Wikipedia, answer to the question whether such a person exists is unknown in the context of Wikipedia since Wikipedia does not have complete knowledge about the world).

- *The meaning of "true" itself may be different in different contexts.* For example, an description logic statement is true against an ontology only if *all* models of the ontology entails the statement, whereas a statement is true against a logic programming knowledge base if *some* selected set of models (e.g., minimal Herbrand models) entail it. Thus, the meanings of truth in a DL-based context (e.g., OWL) and a LP-based context are not necessarily the same.

In this paper, we, instead, introducing a new context formalism based on the notion of "jurisdiction" based on the following assumptions about contexts:

- When we say a statement is related to a context, we do not necessarily mean the statement is true in the context, rather, we mean the context has the jurisdiction to interpret the meaning of the statement. If a context has no jurisdiction over a statement, the statement shall not be interpreted in that context[3].

- A context may make explicit description of the *semantic assumptions* it makes and the precise meaning of truth in that context. We call such a description as the *institution* of the context.

- A context maybe a *rich object* that has descriptions about its properties (such as provenances) and relations to other contexts.

For these goals, we extend [38] by introducing a new relation "isin" (is in) to indicate the jurisdiction relation between a statement and a context:

$$\mathsf{isin}(c, \alpha)$$

where c is a context of the statement α, i.e., α can be interpreted using the semantic assumptions made in the institution of c (see more on institutions in Section 4). Note, in general, we do not have

$$\mathsf{isin}(c, \alpha) \rightarrow \mathsf{ist}(c, \alpha)$$

However, since a statement is only true in an applicable context, the reverse relation is always true:

$$\mathsf{ist}(c, \alpha) \rightarrow \mathsf{isin}(c, \alpha)$$

An "isin" relation can be negated or quantified same as other statements. For example,

$$\neg\mathsf{isin}(c, \alpha)$$

means that α is not applicable in the context c, thus $\mathsf{ist}(c, \alpha)$ is not a valid formula. When we see such a relation, either explicitly stated or inferred using the context's properties and axioms, we will be able to prevent using the statement in a wrong context ("out of context").

The next statement, using universal quantification, says that if the negation of a statement is a Propositional Logic statement, then it is also a Propositional statement:

$$\forall\alpha, \mathsf{isin}(pl, \neg\alpha) \rightarrow \mathsf{isin}(pl, \alpha)$$

where pl stands for the context of Propositional Logic.

Note that in Propositional Logic of Context (PLC) [19], a logic based on the framework of [38], consistency of contexts requires that

$$\forall\alpha, \mathsf{ist}(c, \neg\alpha) \rightarrow \neg\mathsf{ist}(c, \alpha)$$

This shows a clear difference between the ist relation and the isin relation.

2.2 Context Constructors and Axioms

Similar to lifting axioms in [38], there are many useful relations between contexts that can be captured by *context constructors and axioms.*

Union. A union constructors "$\vee$", e.g., in

$$\mathsf{isin}(c_1 \vee c_2, \alpha)$$

means that α can be interpreted by either c_1 or c_2. For example, an OWL DL ontology O can be interpreted either by the OWL DL semantics (captured by a context s_{DL}) or the OWL Full Semantics (captured by a context s_{Full}):

$$\mathsf{isin}(s_{DL} \vee s_{Full}, O)$$

Intersection. An intersection constructor, e.g., in

$$\mathsf{isin}(c_1 \wedge c_2, \alpha)$$

[1]In this paper, instead of using "proposition", we use "knowledge statement", or just "statement", as it is more commonly used in the Semantic Web community.

[2]Here we use English statements for ease of understanding. Equivalent statements can be easily made using an ontology language such as OWL.

[3]An analogy to this in natural language is that an English sentence should only be interpreted using the grammar of English, but not the grammar of French, and that being under the jurisdiction of English grammar does not necessarily imply the truth of that sentence in English.

creates a new context that has properties from both c_1 and c_2. For example, Bart Simpson is a child appeared in both South Park (context "*sp*") and The Simpsons (context "*ts*"), therefore we have:

$$\mathsf{isin}(sp \wedge ts, \texttt{Child}(\texttt{BartSimpson}))$$

Extension. A context c_1 may extend another context c_2, denoted as $c_1 \Rightarrow c_2$, such that it inherits institutional properties of c_2 (e.g., c_2's semantic assumptions), possibly with some additional properties of its own. c_1 is said a subcontext of c_2 and c_2 is a supercontext of c_1. Therefore, we have

$$(c_1 \Rightarrow c_2 \wedge \mathsf{isin}(c_1, \alpha)) \rightarrow \mathsf{isin}(c_2, \alpha)$$

(if α is interpretable in c_1 then it is interpretable in c_2)

$$(c_1 \Rightarrow c_2 \wedge \mathsf{ist}(c_1, \alpha)) \rightarrow \mathsf{ist}(c_2, \alpha)$$

(if α is true in c_1 then it is also true in c_2)

The reverse of the two context axioms are not necessarily true.

The extension relation is transitive, thus

$$((c_1 \Rightarrow c_2) \wedge (c_2 \Rightarrow c_3)) \rightarrow (c_1 \Rightarrow c_3)$$

We always have that

$$c_1 \wedge c_2 \Rightarrow c_1 \text{ and } c_1 \Rightarrow c_1 \vee c_2$$

Note that c_1 may not necessarily inherits other properties of c_2, e.g., provenances.

Nesting. An isin assertion itself can be stated in another "outer" context. For example, "Wikipedia says that in the television series South Park, Eric Cartman lives in the place South Park " can be represented as

$$\mathsf{isin}(wikipedia, \mathsf{isin}(sp, \texttt{livesIn}(\texttt{EricCartman}, \texttt{SouthPark})))$$

where *wikipedia* is the context of Wikipedia, and *sp* is the context of the television series South Park.

In general, we assume that there is a universal context c_0 as the default outer context of all other contexts, and it can be omitted whenever necessary.

Note that context nesting is different from context extension: an extension transfers truth and jurisdiction of a statement from a subcontext to a supercontext, whereas nesting does not transfer these to the outer context. Therefore,

$$\mathsf{isin}(wikipedia, \texttt{livesIn}(\texttt{EricCartman}, \texttt{SouthPark}))$$

does not follow from the previous assertion.

Incompatibility. Context incompatibility declarations can prevent using a statement out of context. For a context c, $\neg c$ stands for the union of all contexts that are incompatible with c. We have

$$\mathsf{isin}(\neg c, \alpha) \leftrightarrow \neg \mathsf{isin}(c, \alpha)$$

Therefore, we can express "c_1 is incompatible with c_2" as

$$\mathsf{isin}(c_1, \alpha) \rightarrow \mathsf{isin}(\neg c_2, \alpha)$$

or in short form as $c_1 \rightarrow \neg c_2$

We can easily see that if a context c_1 has a supercontext that is incompatible with c_2, then c_1 must be also incompatible with c_2:

$$((c_1 \Rightarrow c') \wedge (c' \rightarrow \neg c_2)) \rightarrow c_1 \rightarrow \neg c_2$$

In the next section, we will show more examples on inferring context incompatibility based its provenance properties.

Compatibility. Compatibility declarations transfer jurisdiction from one context to another context. "c_1 is compatible with c_2", denoted as $c_1 \rightarrow c_2$, means that

$$\mathsf{isin}(c_1, \alpha) \rightarrow \mathsf{isin}(c_2, \alpha)$$

Compatibility is weaker than extension since it only transfers jurisdiction but not truth of statements.

The set of context constructors and axioms is not meant to be complete. Other useful *context description languages* may be designed.

2.3 Context IRIs and Dereferencing

On the Semantic Web, a context can be represented as a Web resource and identified with an IRI (Internationalized Resource Identifier, a generalization form of URI and URL). A context description document, either formally described as a set of context axioms or informally stated as a human-readable document, may be dereferenced at the IRI. In addition, the dereferenced document may provide other information about the context, such the provenance and institution descriptions of the context (as will be outlined later in the paper).

3. PROVENANCES OF CONTEXTS

Contexts in our framework are *rich objects* such that they may have properties. In particular, a set of common and important properties are the *provenance* of a context, including the aspects of temporal (when), spatial (where), agent (who), casual (why) and other properties. Recent advances in provenance modeling (e.g., PML [22, 39]) allow us to precisely describe provenances and conduct inference with provenance knowledge[4]. The goal of this section is not to propose or advocate a particular provenance model for describing contexts – this decision is best left to domain experts who model the contexts. Instead, we demonstrate several typical scenarios when provenance information can leverage inferences about contexts.

Quoting. Identifying a context using its provenance information can help us to realize quoting as supported by the N3 Logic [7] and Named Graphs [20]. For example, in the N3 Logic (the modeling using named graphs is similar), we may use quoted formulae such as:

```
:wikipedia :says{
    :sp :says {
        :EricCartman :livesIn :SouthPark }}.
```

In our context model "wikipedia" and "sp" are represented as two contexts (as shown in the last section), and we can attach provenance information to these contexts. For example, we may add the following RDF statements about "wikipedia" and "sp":

```
:wikipedia :sourcePage
     "http://en.wikipedia.../Eric_Cartman"^^xsd:iri .
:wikipedia :date "2010-03-25"xsd:date .
```

[4]http://www.w3.org/2005/Incubator/prov/wiki/Provenance_Survey lists several survey papers on provenance.

```
:wikipedia :author user:JohnSmith .
:wikipedia :revision "352615356"^^xsd:intger .
......
:sp rdfs:comment "South Park context" .
:sp :author "Trey Parker" .
:sp :author "Matt Stone" .
:sp context:isIn :wikipedia .
......
```

Where "`context:isIn`" is a hypothetical property name to represent the isin relation.

Note that there is an important difference between quoting by graph ids as in [7, 20] and quoting using context relations. A context of a statement does not need to be the physical location where the statement is made, nor it must be a graph, e.g., the "sp" context above refers to a conceptual context with no corresponding graph. This separation of the conceptual context and the physical location of a statement offers several advantages:

- It offers a flexible way to describe context. For example, while the editors of Wikipedia's pages about South Park may not be Trey Parker and Matt Stone themselves (thus, they are not the authors of the physical location of the statement), we are still able to correctly credit them as the creators of the South Park context.
- It leverages data integration. Knowledge statements from different graphs may share the same context, then we will immediately know that they can be combined context-safely.
- It allows us to associate multiple contexts to a statement whereas in N3 Logic or named graphs a statement can only reside in one graph. For example, we may associate to the statement `livesIn(EricCartman, SouthPark)`, in addition to *sp*, also contexts "*us*" (United States) and "fol" (First Order Logic).

Inferring (In)compatibility. Provenance information may be used in determining whether a statement is applicable in a context, or a context is (in)compatible with another context. For example, we may have the following statements saying that news from CNN should not be interpreted in the contexts that are from the Fox News:

$$\forall c_1, c_2, \texttt{hasSource}(c_1, CNN) \land \texttt{hasSource}(c_2, FoxNews) \rightarrow (c_1 \rightarrow \neg c_2)$$

where `hasSource` relates a contexts to its source.

The next example shows that annual reports of mutual funds can be put together for comparison only if they are from the same year

$$\forall c_1, c_2, \exists y, \texttt{hasYear}(c_1, y) \land \texttt{hasYear}(c_2, y) \land \texttt{AnnualReport}(c_1) \land \texttt{AnnualReport}(c_2) \rightarrow (c_1 \rightarrow c_2) \land (c_2 \rightarrow c_1)$$

Selective Importing. The current importing mechanism in OWL has the implicit assumption that all ontologies in the importing transitive closure are compatible to other each such that a union of them can be made and the importer ontology is interpreted under this union. However, this is not always desired as importing is often used as citation whereas the "cited" content is not necessarily always true in the importer's context (e.g., in the case of citing for critique). Also, since importing can be transitive but the trust of content is not always transitive, using an indirectly imported ontology may result in unintended consequences.

Using the context mechanism, we will be able to realize selective importing such that only trusted ontologies in the importing transitive closure is taken into account. For example, the next strategy says that only ontologies published by an educational organization (with domain name ".edu") should be used. We assume, if an ontology does not declare a context where it is in, it uses a default context with a property `iri` which is the ontology's iri; `imports`$^+$ is the importing transitive closure relation; `topDomain` is a function that parses the top-level domain of an iri.

$$\mathsf{isin}(c, O) \land \texttt{imports}^+(O, O') \land \mathsf{isin}(c', O') \land \texttt{iri}(c', x) \land (\texttt{topDomain}(x) == "edu") \rightarrow \mathsf{isin}(c, O')$$

4. INSTITUTIONS OF CONTEXTS

4.1 Modeling Semantic Assumptions Using Institutions

The `isin` relation does not specify whether a statement is true in a context. This is left to be validated using the *institution* of the context, i.e., the set of semantic assumptions made in the context. The term "institution" is adopted under the influence of the institution theory [27] which specifies a framework for abstract description of a logic system. Note that a description of an institution does not necessarily be a formal or machine-readable description (while this is desired and more details are discussed in the next subsection). For example, N3 Logic [7] currently does not have a formal semantics; the OWL syntax and semantic document [41] gives a formal yet only human-readable description for OWL [40] and is currently implicitly used as the default institution document for OWL ontologies. In particular, if a context is not logic-dependent, it may have no associated institution.

Basically, an institution description specifies the following common aspects of a logic system:

- A signature, i.e., some vocabulary that can be used to construct sentences;
- A sentence generation grammar using the signature;
- A mapping from the signature to the models of the institution;
- A satisfaction relation between sentences and models.

These can be formally describe based on the category theory as given in Def. 1 (for basic notions in the category theory, cf. [5]):

Definition 1. ([27] Definition 1) An **institution** $\mathbb{I}$ consists of

1. a category **Sign**, whose objects are called **signatures**,
2. a functor $\mathsf{SEN} : \mathbf{Sign} \rightarrow \mathbf{Set}$, giving for each signature $\Sigma \in |\mathbf{Sign}|$ a set of **sentences** of the signature,
3. a functor $\mathsf{MOD} : \mathbf{Sign} \rightarrow \mathbf{Cat}^{op}$, giving for each signature $\Sigma \in |\mathbf{Sign}|$ a category whose objects are called Σ-models, and whose arrows are called Σ-(model) **morphisms**,
4. a relation $\models_\Sigma \subseteq |\mathsf{MOD}(\Sigma)| \times \mathsf{SEN}(\Sigma)$ for each $\Sigma \in |\mathbf{Sign}|$, called Σ-**satisfaction**.

such that for each morphism $\phi : \Sigma \to \Sigma'$ in **Sign**, the **Satisfaction Condition** holds:

$$m' \models_{\Sigma'} \mathsf{SEN}(\phi)(e) \text{ iff } \mathsf{MOD}(\phi)(m') \models_{\Sigma} e$$

For example, OWL DL is an institution where the signature is the set of all named classes, properties and individuals; sentences are constructed following the grammar given in [41]; its models are the set of all first-order models; the satisfaction relation is given in [41] under the open world assumption and non-unique name assumption. This institution can be used as the default institution of an "OWL DL" context which handles all syntactically valid OWL DL ontologies. Similarly, we may have the RDFS institution and the OWL Full institution.

The institution theory also allows us to formally describe syntactical and semantic relations between two different institutions using institution morphisms:

DEFINITION 2.: ([27] Definition 32) Let $\mathbb{I}_1 = \langle \mathbf{Sign}_1, \mathsf{SEN}_1, \mathsf{MOD}_1, \models^1 \rangle$ and $\mathbb{I}_2 = \langle \mathbf{Sign}_2, \mathsf{SEN}_2, \mathsf{MOD}_2, \models^2 \rangle$ be two institutions. An **institution morphism** $\Phi : \mathbb{I}_1 \to \mathbb{I}_2$ consists of

1. A functor $f : \mathbf{Sign}_1 \to \mathbf{Sign}_2$
2. A natural transformation $\alpha : f \circ \mathsf{SEN}_2 \Rightarrow \mathsf{SEN}_1$
3. A natural transformation $\beta : \mathsf{MOD}_1 \Rightarrow f^{op} \circ \mathsf{MOD}_2$

such that the following Satisfaction Condition holds:

$$m \models^1_{\Sigma} \alpha_{\Sigma}(e) \text{ iff } \beta_{\Sigma}(m) \models^2_{f(\Sigma)} e$$

for any Σ-model m from $\mathbb{I}_1$ and any $f(\Sigma)$-sentence e from $\mathbb{I}_2$.

For readers who are not familiar with the category theory, the above definition can be understood as a systematic mapping of the vocabularies, the sentence grammars and the models between the two institutions under some satisfaction preservation conditions. For example, the RIF RDF and OWL Compatibility document [23] describes an embedding of RDF in RIF, while it does not directly use institution theory notions, covers the above aspects of institution mapping using a formal, human-readable description.

Associating an explicitly stated institution to a context brings several benefits:

- It separates of the making of a statement and that asserting the statement is true, which is useful to enable quoting, citing without supporting and expressing uncertainty, just for a few examples.
- It enables us to connect knowledge bases stated in different logics or using different semantic assumptions.
- It may better guide tools to process the ontology in an intended way. For example, one may publish an syntactically valid OWL-DL ontology but wish tools to use it as an OWL Full ontology (e.g., instead of performing tableau-based inference, perform a rule-based inference for the ontology); this can be realized by associating the OWL Full institution to the context of the ontology[5].
- It facilitates extending an existing institutions in a modular and explicit way. For example, one may want to use OWL-DL but also use the unique name assumption (UNA); this may be realized by defining an UNA context and institution, and then declare that the ontology uses an intersection context of the OWL-DL context and the UNA context.

[5]For a discussion of intended semantics of an OWL document, cf. `http://www.w3.org/2007/OWL/tracker/issues/111`

4.2 Machine-readable Institution Specifications

While most of institution descriptions on the Semantic Web is formal, few of them is machine-readable. A machine-readable definition of the syntax and semantics of an institution will greatly facilitate the automatic validation and processing of contexts that use the institution. A notable exception is RIF-BLD (Basic Logic Dialect) [8], which, as a specialization of RIF-FLD (The Framework for Logic Dialects) [9], is provided with a formal syntactic, semantic and XML serialization framework. In fact, RIF-FLD offers a comprehensive framework to specify "both syntax and semantics...through a number of mechanisms that are commonly used for various logic languages" [9]. RIF-FLD has the following main components:

- Syntactic framework, which defines the formal presentation syntax of the logic, e.g., alphabet, symbol space and well-formed formulas;
- Semantic framework, which specifies a model-theoretical semantics of the logic and relates the syntax to models;
- XML serialization framework, which defines the general principles for specifying concrete XML-based syntaxes of the logic.

We believe that the generic nature of RIF-FLD makes it an ideal candidate for creating machine-readable institution specifications. This has been evidenced by that various non-official dialects have defined using this framework, e.g., RIF-URD (Uncertainty Rule Dialect) [48] and RIF-CASPD (Core Answer Set Programming Dialect) [32].

Another potential approach to design an institution specification language is to extend Common Logic[6] with a machine-readable syntax. CL also allows the definition of a variety of different dialects, including FOL and even higher-order logics.

5. RELATED WORK

Contexts have been extensively studied in AI and other fields. We can only discuss the most relevant work here due to page limits. For surveys on contexts in AI, cf. [14, 15, 1, 35] and for a survey on context representation for the Semantic Web pre-2004 cf. [10]. The Context Conference[7] is also a good source about context research.

5.1 Contexts in AI

McCarthy-style Contexts: Our work extends McCarthy's work on context modeling [37, 38] by separating the notions of truth-based contexts and jurisdiction-based contexts. We have shown that such a separation is useful for Semantic Web applications where truth of a statement is often unknown or meaningless when it is applied in a wrong context.

[6]http://www.common-logic.org

[7]`http://www.informatik.uni-trier.de/~ley/db/conf/context/index.html`

Guha [28] has extended McCarthy's notion of context and applied it in building the CYC system [34]. Knowledge statements in CYC is divided into *microtheories* which serve as the contexts of the statements. A microtheory, similar to contexts in [38], is an object that has a name and can be organized in a microtheory hierarchy. Guha's approach shares the same limitations as McCarthy's to be used for Semantic Web.

Buvac and others[8] applied McCarthy's framework in various logics, leading to the study of Propositional Logic of Context (PLC) [19, 17] and Quantificational Logic of Context [16, 36]. Buvac showed that the "ist" relation is essentially a modal operator, and a formal semantics and calculus in the modal logic fashion can be given for McCarthy-style contexts in propositional logics and quantificational (predicate) logics. In fact, Buvac and Mason [18] have shown PLC can be reduced to propositional multi-modal logic. Buvac's approach requires all contexts to be in the same institution whereas this is not required in our approach.

MultiContext Logics. Multicontext logics[9] [26] is a family of logics based on two principles:

- Locality - In inference, only partial knowledge is available and this part is call the context for the inference process.
- Compatibility - There is compatibility among the reasoning performed in different contexts.

A multi-context system (MCS) is formally described using the Local Models Semantics [25] and its proof theory (a generalization of natural deduction) is composed of internal rules (for intra-context inference and bridge rules (for inter-context inference). Multicontext logics influenced Distributed First Order Logics [24] and Distributed Description Logics (DDL) [11], with the latter has a close relation to Semantic Web applications.

Bouquet and Serafini [13, 42] have compared multicontext logics and McCarthy-style contexts and have shown that lifting axioms are special forms of bridge rules in MCS, and in general, McCarthy-style contexts are less expressive than the multicontext logics.

Applying the multicontext logics in the Semantic Web, while is conceptually straightforward, has some practical issues in specifying compatibility relations between contexts. Two well-known problems are that knowledge can not be transitively reused in DDL and bridge rules offer only limited expressivities to relate ontologies since they require disjoint vocabularies in different ontologies [4].

Contexts based on Situation Theory. Akman and Surav [3] used Situation Theory [6] to model contexts. A situation is a limited viewpoint of the world from an agent. A context is a situation that contains a set of ground knowledge assertions (called "infons" in the theory) and constraints for deriving new facts. McCarthy-style context assertions can be represented as infons such as:

$$\texttt{ist}(c, p(x)) \Rightarrow \ll p_c, x, 1 \gg$$

where p_c is a new predicate (context c's version of p), and "1" means $p_c(x)$ is true in the situation.

[8] http://www-formal.stanford.edu/buvac/

[9] http://www.dit.unitn.it/~context/

The situation theory based approach may face an explosion blow-up of newly introduced predicates when there are many predicates and contexts. In addition, the lack of a natural deduction system in [3] is a critical limitation for its practical use.

5.2 Context Modeling in Semantic Web

Guha and others [29] applied McCarthy-style contexts for Semantic Web use, targeting aggregation of independently published data. This proposal shares some common properties with our framework, such that each document has a context which can be identified by an IRI/URL. It provides a small ontology to describe contexts, and an alternative approach to provide an extended RDF model theory for introducing contexts.

Stoermer[44, 45] also applied McCarthy-style contexts for RDF context management. For this purpose, this work introduces a Context Relations Ontology (CRO) without adding new language features to RDF (which is different from [29])

Since both [29] and [44, 45] are based on the ist relation, inherent limitations of the McCarthy-style contexts also present in these proposals.

C-OWL [12] is an extension of OWL based on Distributed Description Logics. The expressivity of C-OWL is limited to be used largely as an ontology mapping language. For example, an "into" bridge rule can be used to establish subclass-like relationship between classes in two ontologies. In addition, since a context is not an object in C-OWL, one can not assert provenance or other properties about a context.

Several other researchers have applied context modeling in semantic desktops [30], information sharing and privacy protection [21], data integration [46] and semantic wikis [33, 47]. These works' goals are not providing a generic context modeling framework, which is the focus of our paper.

6. CONCLUSIONS

We investigated extending McCarthy's context framework to address context modeling on the Semantic Web. We show that by introducing the notion of context jurisdiction, we can model many scenarios that are no expressible using the McCarthy's original framework, e.g., citation without supporting, asserting statements with unknown truth values, and preventing interpreting statements in wrong contexts. We showed that by using provenance information of a context we are able to realize quoting, incompatibility inference and selective importing. We also discussed making (usually implicit) semantic assumptions used in an ontology explicit as logic institutions and presented practical approaches to specify an institution.

This paper is only the first step towards an expressive context modeling framework. Many details of the framework are to be investigated in the future, including the following:

- A formal semantics to specify the precise meaning of the isin relation and to derive a natural deduction system for the framework.
- A concrete syntax for expressing contexts that can work with RDF and OWL.
- An investigation into how to use policy languages to manage multiple applicable contexts of an ontology and to realize situation-aware context selection.

- An investigation into use of the context framework to address some common modeling problems. One such problem is modeling integrity constraints [43] which may be modeled as an extension of the standard RDF/OWL context with some variations of the Closed World Assumption. We are also interested in studying the application of contexts in modeling modular ontologies [4].

Acknowledgments: This work is supported in part by NSF #0524481, DARPA #FA8650-06-C-7605, #FA8750-07-D-0185, #55-002001, #F30602-00-2-0579, and ITA project W911NF-06-3-0001.

7. REFERENCES

[1] Varol Akman. *Context in Artificial Intelligence: A Fleeting Overview.* McGraw-Hill, Milano, 2002.

[2] Varol Akman and Mehmet Surav. Steps toward formalizing context. *AI Magazine*, 17(3):55–72, 1996.

[3] Varol Akman and Mehmet Surav. The use of situation theory in context modeling. *Computational Intelligence*, 13(3):427–438, 1997.

[4] Jie Bao, Doina Caragea, and Vasant Honavar. On the semantics of linking and importing in modular ontologies. In *International Semantic Web Conference (ISWC)*, pages 72–86, 2006.

[5] Michael Barr and Charles Wells, editors. *Category theory for computing science, 2nd ed.* Prentice Hall International (UK) Ltd., Hertfordshire, UK, UK, 1995.

[6] J Barwise. Situations and small worlds. In *In The Situation in Logic, number 17 in CSLI Lecture Notes*, pages 79–92, 1987.

[7] Tim Berners-Lee, Dan Connolly, Lalana Kagal, Yosi Scharf, and Jim Hendler. N3logic: A logical framework for the world wide web. *TPLP*, 8(3):249–269, 2008.

[8] Harold Boley and Michael Kifer. RIF Basic Logic Dialect. Candidate Recommendation CR-rif-bld-20091001, World Wide Web Consortium, Oct 2009.

[9] Harold Boley and Michael Kifer. RIF Framework for Logic Dialects. Candidate Recommendation CR-rif-fld-20091001, World Wide Web Consortium, Oct 2009.

[10] Elena Paslaru Bontas. Context representation and usage for the semantic web: A state of the art. Technical Report B-04-30, Freie Universität Berlin, `http://www.inf.fu-berlin.de/inst/pubs/tr-b-04-30.abstract.html`, 2004.

[11] Alexander Borgida and Luciano Serafini. Distributed description logics: Assimilating information from peer sources. *Journal of Data Semantics*, 1:153–184, 2003.

[12] Paolo Bouquet, Fausto Giunchiglia, Frank van Harmelen, Luciano Serafini, and Heiner Stuckenschmidt. C-OWL: Contextualizing ontologies. In Dieter Fensel, Katia P. Sycara, and John Mylopoulos, editors, *International Semantic Web Conference*, volume 2870 of *Lecture Notes in Computer Science*, pages 164–179. Springer, 2003.

[13] Paolo Bouquet and Luciano Serafini. On the difference between bridge rules and lifting axioms. In Patrick Blackburn, Chiara Ghidini, Roy M. Turner, and Fausto Giunchiglia, editors, *CONTEXT*, volume 2680 of *Lecture Notes in Computer Science*, pages 80–93. Springer, 2003.

[14] Patrick Brézillon. Context in artificial intelligence: I. a survey of the literature. *Computers and Artificial Intelligence*, 18(4), 1999.

[15] Patrick Brézillon. Context in artificial intelligence ii. key elements of contexts. *Computers and Artificial Intelligence*, 18(5), 1999.

[16] Sasa Buvac. Quantificational logic of context. In *AAAI/IAAI, Vol. 1*, pages 600–606, 1996.

[17] Sasa Buvac, Vanja Buvac, and Ian A. Mason. The semantics of propositional contexts. In *ISMIS*, pages 468–477, 1994.

[18] Sasa Buvac, Vanja Buvac, and Ian A. Mason. Metamathematics of contexts. *Fundam. Inform.*, 23(2/3/4):263–301, 1995.

[19] Sasa Buvac and Ian A. Mason. Propositional logic of context. In *AAAI*, pages 412–419, 1993.

[20] Jeremy J. Carroll, Christian Bizer, Patrick J. Hayes, and Patrick Stickler. Named graphs, provenance and trust. In *WWW*, pages 613–622, 2005.

[21] Harry Chen, Timothy W. Finin, and Anupam Joshi. Semantic web in the context broker architecture. In *PerCom*, pages 277–286, 2004.

[22] Paulo Pinheiro da Silva, Deborah L. McGuinness, and Richard Fikes. A proof markup language for Semantic Web services. *Inf. Syst.*, 31(4-5):381–395, 2006.

[23] Jos de Bruijn. RIF RDF and OWL Compatibility. Candidate Recommendation CR-rif-rdf-owl-20091001, World Wide Web Consortium, Oct 2009.

[24] C. Ghidini and L. Serafini. *Frontiers Of Combining Systems 2, Studies in Logic and Computation*, chapter Distributed First Order Logics, pages 121–140. Research Studies Press, 1998.

[25] Chiara Ghidini and Fausto Giunchiglia. Local models semantics, or contextual reasoning=locality+compatibility. *Artificial Intelligence*, 127(2):221–259, 2001.

[26] Fausto Giunchiglia and Fausto Giunchiglia. Contextual reasoning. *Epistemologia, special issue on I Linguaggi e le Macchine*, 345:345–364, 1992.

[27] Joseph A. Goguen and Rod M. Burstall. Institutions: Abstract model theory for specification and programming. *J. ACM*, 39(1):95–146, 1992.

[28] Ramanathan V. Guha. *Contexts: a formalization and some applications*. PhD thesis, Stanford University, 1991.

[29] Ramanathan V. Guha, Rob McCool, and Richard Fikes. Contexts for the semantic web. In Sheila A. McIlraith, Dimitris Plexousakis, and Frank van Harmelen, editors, *International Semantic Web Conference*, volume 3298 of *Lecture Notes in Computer Science*, pages 32–46. Springer, 2004.

[30] Tom Heath, Enrico Motta, and Martin Dzbor. Context as a foundation for a semantic desktop. In *Semantic Desktop Workshop*, 2005.

[31] Jim Hendler and Tim Berners-Lee. From the Semantic Web to social machines: A research challenge for AI on the World Wide Web. *Artificial Intelligence*, 174(2):156 – 161, 2010. Special Review Issue.

[32] Stijn Heymans and Michael Kifer. RIF Core Answer

Set Programming Dialect. Editor's Draft RIF-CASPD, World Wide Web Consortium and The Rule Markup Initiative, Dec 2009.

[33] Malte Kiesel, Sven Schwarz, Ludger van Elst, and Georg Buscher. Mymory: Enhancing a semantic wiki with context annotations. In *ESWC*, pages 817–821, 2008.

[34] Douglas B. Lenat. Cyc: A large-scale investment in knowledge infrastructure. *Commun. ACM*, 38(11):32–38, 1995.

[35] William Loyola. Comparison of approaches toward formalizing context: Implementation characteristics and capacities. *Electronic Journal of Knowledge Management*, 5(2):203–214, 2007.

[36] Selene Makarios. A model theory for a quantified generalized logic of contexts. Technical Report KSL-06-08, Knowledge Systems, AI Laboratory, 2006.

[37] John McCarthy. Notes on formalizing context. In *IJCAI*, pages 555–562, 1993.

[38] John McCarthy and Sasa Buvac. Formalizing context (expanded notes). Technical report, Stanford, CA, USA, 1994.

[39] Deborah L. McGuinness, Li Ding, Paulo Pinheiro da Silva, and Cynthia Chang. PML 2: A Modular Explanation Interlingua. In *ExaCt*, pages 49–55, 2007.

[40] Deborah L. McGuinness and Frank van Harmelen. OWL Web Ontology Language Overview. Technical Report REC-owl-features-20040210, W3C, 2004.

[41] P.F. Patel-Schneider, P.Hayes, and I. Horrocks. Web Ontlogy Language (OWL) Abstract Syntax and Semantics. http://www.w3.org/TR/owl-semantics/, February 2004.

[42] Luciano Serafini and Paolo Bouquet. Comparing formal theories of context in ai. *Artif. Intell.*, 155(1-2):41–67, 2004.

[43] Evren Sirin and Jiao Tao. Towards integrity constraints in owl. In *OWLED*, 2009.

[44] Heiko Stoermer. Introducing Context into Semantic Web Knowledge Bases. In *Proceedings of the CAISE*06 Doctoral Consortium*, June 2006. http://dme.uma.pt/caise06dc/papers/Stoermer.pdf.

[45] Heiko Stoermer, Paolo Bouquet, Ignazio Palmisano, and Domenico Redavid. A context-based architecture for rdf knowledge bases: Approach, implementation and preliminary results. In *RR*, pages 209–218, 2007.

[46] Philip Tan, Stuart E. Madnick, and Kian-Lee Tan. Context mediation in the semantic web: Handling owl ontology and data disparity through context interchange. In *SWDB*, pages 140–154, 2004.

[47] Ludger van Elst, Malte Kiesel, Sven Schwarz, Georg Buscher, Andreas Lauer, and Andreas Dengel. Contextualized knowledge acquisition in a personal semantic wiki. In *EKAW*, pages 172–187, 2008.

[48] Jidi Zhao and Harold Boley. Uncertainty treatment in the rule interchange format: From encoding to extension. In *URSW*, 2008.