A Formal Context Representation Framework for Network-Enabled Cognition

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***Abstract*—Network-accessible resources are inherently contextual with respect to the specific situations (e.g., location and default assumptions) in which they are used. Therefore, the explicit conceptualization and representation of contexts is required to address a number of problems in Network-Enabled Cognition (NEC). We propose a context representation framework to address the computational specification of contexts. Our focus is on developing a formal model of context for the unambiguous and effective delivery of data and knowledge, in particular, for enabling forms of automated inference that address contextual differences between agents in a distributed network environment. We identify several components for the conceptualization of contexts within the context representation framework. These include jurisdictions (which can be used to interpret contextual data), semantic assumptions (which highlight the meaning of data), provenance information and inter-context relationships. Finally, we demonstrate the application of the context representation framework in a collaborative military coalition planning scenario. We show how the framework can be used to support the representation of plan-relevant contextual information.**

I. Introduction

Network technologies have fundamentally changed the ways people search for information, seek for inspiration, make decisions, disseminate discoveries, and, finally, how people think and perform cognitive tasks. The notion of the network-extended mind [Smart et al., 2010] proposes that the informational and technological elements of a network system can constitute part of the material supervenience base for a human agent's mental states and processes. Thus, network systems can do more than just augment cognition[1]; they can also constitute part of the physical machinery that makes mind and cognition mechanistically possible. Furthermore, the large-scale social interaction enabled by networks also encourages new forms of network-enabled cognitive problem solving. One example is the "Human flesh search engine" [Wang et al., 2009] (or Human-computer Search Engine), which is a research phenomenon leveraged by massive Web-based human collaboration using both online and offline knowledge sources[2]. It has been argued that networks, and in particular the World Wide Web, could enable the kind of massive problem solving that leads to the realization of some sort of *Social Machine* [Berners-Lee and Fischetti, 1999], [Hendler and Berners-Lee, 2010].

One of the important differences between network-accessible resources and one's own individually-created resources, is that network-accessible resources are often generated by another person. This means network-accessible resources are inherently contextual, and their interpretations may be different or meaningless if they are "taken out of context", i.e., used in a context that is different from the one in which they were created. For example, when a scientist does research about climate change patterns in the summer of 2000, the data from the United States and the data from Australia both have different temporal meanings implied by their location difference, even if they are both labeled as "summer 2000" data (this is because of the seasonal differences between the northern and southern hemisphere: Summer in the US is Winter in Australia). As another example, if we want to verify a person's affiliation using Web search and can't find the person's name at the asserted affiliation's website, then whether we can come to the conclusion that the asserted affiliation is false or not depends on on whether we adopt an open world assumption (i.e., the website may not have complete knowledge about all personnel) or a closed world assumption (i.e., the website has complete knowledge). Here the adopted semantic assumptions constitute a user's context, which may be different from the publisher's original context (for instance, the website may have had complete information about personnel when it was first published, but such information subsequently became obsolete). However, contexts are often embedded in application programs, or they are implied by application- or community-specific agreements. To facilitate NEC, we need a better means for representing context and supporting the automatic- or semi-automatic- processing of contexts associated with network-accessible resources.

In this paper, we apply a generic context representation

[1] In this paper, we use the term "cognition" to refer to an information processing view of an individual's psychological functions.

[2] It's notable that Google China developed a dedicated Human flesh search engine (http://www.google.cn/intl/zh-CN/renrou/index.html)

framework [Bao et al., 2010b] to address the computational aspects of context in NEC. Our focus is on developing a formal model of contexts for the unambiguous and effective delivery of data and knowledge, in particular, for enabling automated inference that addresses contextual differences between agents in a distributed network environment. We identify several components for the conceptualization of contexts, including: a) the notion of jurisdiction to interpret contextual data; b) the formal representation of semantic assumptions associated with the data as logical institutions; c) provenances of contexts, e.g., who created the data and when was the data created; and 4) relations between contexts (e.g., an incompatibility between specific contexts).

In the current paper, we demonstrate the application of the context representation framework with respect to the ITA Collaborative Planning Model (CPM) [Allen et al., 2008]. The CPM consists of a logical component representing the concepts of collaborative planning and replanning, together with a meta component that represents the processes, collaborations, and information flows that occur within different planning doctrines. We show that the proposed context model has the potential to support the representation of context information within the CPM. For example, rationale information is an important aspect of the plan development process, and the representation of this information as context information can be used to support the appropriate interpretation of planning decisions.

In the following, we first explain the theory of Network-Enabled Cognition and the important role of context representation (see Section II); in Section III, we introduce a generic context representation framework for the Web, and, in particular, for the Semantic Web; in Section IV, we show that the model can be applied to the ITA CPM (Collaborative Planning Model). Finally, we discuss related work and conclusions in Section V and VI, respectively.

II. Network-Enabled Cognition and Contexts

The advent of large-scale information networks, such as the World Wide Web, has transformed our access to information content, and this may have a number of implications for cognitive processing, both at the individual and collective (social) levels (see [Huynh et al., 2010]). In order for networks (and the information resources that they make available) to facilitate cognitive processing, however, we need to recognize a number of potential problems associated with the exploitation of online information content. One of these problems concerns the notion of context, which we define (in this case) as the information that modifies the meaning of, interpretation of, or response to other information. The point is that in order for online information to support individual and collective cognition, it needs to be used and interpreted correctly. Context information is important here because such information often indicates the correct interpretation of information content (it helps to resolve the precise meaning of some other piece of information) and it often specifies when, where and how the information content should be used.

We exemplify the need for context modeling using our experience with semantic wikis [Bao et al., 2009a]. Semantic wikis are extensions to conventional wikis which exploit semantic technologies in order to support advanced knowledge processing. Common features of semantic wikis include the incorporation of semantic markup into wiki pages, which can be further translated into Semantic Web languages, e.g., RDF and OWL, and querying mechanisms for better knowledge retrieval and propagation. Therefore, semantic wikis are capable of supporting two kinds of knowledge representation: informal knowledge represented as natural language, which is intended for for human consumption, and formal knowledge representations with explicitly defined semantics, which are intended primarily for automated machine processing. Among all the semantic wiki systems currently available, Semantic Mediawiki (SMW) [Krötzsch et al., 2007] is probably the most widely used.

Our experiences with several real-world projects suggest that semantic modeling is much more challenging for human end-users than creating content for a conventional wiki. This is, at least in part, due to the lack of a context model for the knowledge that is asserted in the wiki. A context model indicates *where* to write and find knowledge on SMW, and it preserves the *provenance* information associated with knowledge assertions. The lack of a context model causes a number of problems. For example, SMW (and many other semantic wikis) organizes knowledge into pages, and this highlights two major differences from RDF (Resource Description Framework, a Semantic Web language):

1) In RDF a statement can be asserted anywhere, but in SMW it can only be put on a triple's[3] subject page;

2) An RDF statement can be about arbitrary URIs, but in SMW a triple's subject and predicate can only be a wiki page.

The page-centric organization of SMW has been found to be unsatisfactory for some tasks. For example, we have conducted human tests on the effectiveness of SMW in capturing knowledge and helping fact searching and abductive reasoning[4]. Some of the issues we discovered appeared to be attributable to the lack of a flexible context model in SMW. These include:

- The creation of many trivial, short pages. During the editing process, users often find it tedious to navigate through a couple of pages even for a simple task.
- It is troublesome to describe things (e.g., an external URL) that has no corresponding wiki pages.
- Due to the difficulty of determining where to write knowledge (i.e., the best "subject" pages), many users tend to use the wiki editing functionality without semantic annotations. This often results in long pages containing many facts written in natural languages.
- Many users are confused by query-based pages (a special type of SMW page that automatically queries data from

[3] An RDF document consists of a set of "triples" in the form of `subject, predicate, object`.

[4] See Jie Bao, The Unbearable Lightness of Wiking, a presentation at the SMW Conference 2010, http://www.slideshare.net/baojie_iowa/2010-0522-smwcon

other pages in the wiki). In particular, they do not know how to track the source of the queried results when they want to change a query-based page.

We argue that these issues could be remedied via the introduction of a context model to SMW, such that a triple can be asserted more freely, and its provenance can be tracked during the course of editing and visualizing content. Such a model would allow us to express that "a triple is asserted in a context (e.g., by an author)" without requiring the use of the subject of the triple to locate the triple (as SMW currently does). With a means to explicitly represent context in SMW, we would also be able to find knowledge, e.g., by its creation time or reference source [Bao et al., 2009b], and accommodate multiple, potentially conflicting, points of view as formal knowledge assertions in the wiki.

III. A Generic Context Representation Model

In this section we introduce a generic context representation model [Bao et al., 2010b] for Web resources. The model is focused on the high-level conceptualization of basic components in a context model and a formal representation that would enable the automatic deduction of contexts.

A. Basic Concepts

While the the notion of context has been the focus of considerable attention in Artificial Intelligence (AI) (see [Akman and Surav, 1996] for a survey), there are still no comprehensive studies on the generic and formal representation of contexts of network environments, and in particular, for the Semantic Web. Notable exceptions include C-OWL [Bouquet et al., 2003] and a context model for RDF [Stoermer et al., 2007]. However, these works only cover specific aspects of contexts (for example, C-OWL only addresses contextual ontology mappings).

In previous work [Bao et al., 2010b], we have proposed a formalism for representing contexts on the Web by extending McCarthy's seminal work on context formalization [McCarthy, 1993] (later extended by [McCarthy and Buvac, 1994]). Our proposal is different from previous approaches in that:

- 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 the Web because the truth of a proposition is often not applicable or unknown in a specific context. Our framework 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 [McCarthy and Buvac, 1994]) can be used to state the relations between contexts, thus supporting automated reasoning about contexts.
- While [McCarthy and Buvac, 1994] does not consider semantic assumptions (e.g., the Open World Assumption) in contexts, our framework allows such assumptions to be explicitly stated as institutions [Goguen and Burstall, 1992][5]. This effectively avoids the risk of reusing knowledge outside the situations in which it was originally intended to be used.
- In [McCarthy and Buvac, 1994], a context is an object without a provenance description (i.e., it is not associated with information about who, where or when the object was created). Utilizing recent advances in provenance representation (e.g., PML [da Silva et al., 2006], [McGuinness et al., 2007]), our framework allows a provenance model to be associated with a context.
- Since one ontology may be used in different contexts (each making specific assumptions about the conditions under which the ontology should be used), we allow a context policy to be used in managing contexts (e.g., by describing when a context should be applied).

In [Bao et al., 2010b], we introduced a formal representation of contexts, extending McCarthy's context formalization [McCarthy and Buvac, 1994] (referred as *McCarthy-style contexts* thereafter). This section extends [Bao et al., 2010b] using named graphs [Carroll et al., 2005] as a concrete syntax for representing contexts.

B. Contexts as Jurisdictions

One key notion in [McCarthy and Buvac, 1994] is that contexts are modeled as *first class objects*. A basic relation between a proposition and a context in [McCarthy and Buvac, 1994] 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 approach to context modeling often cannot capture the context of a proposition (often modeled as a knowledge statement in an ontology on the Semantic Web). Some typical problems 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"[6] 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.

[5] A (logical) institution is an abstract description of a logical system, such as its syntax, semantics and model satisfication. For example, OWL DL and RDF can be regarded as two institutions. Two institutions may be used together, e.g., OWL and the UNA (Unique Name Assumption).

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

- *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 theoretical computer science as of today), 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, whether such a person actually 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, a description logic statement is true against an ontology only if *all* models of the ontology entail 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 light of these problems, we introduce a new context formalism based on the notion of "jurisdiction". This formalism is 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 that the context *has the jurisdiction to interpret the meaning* of the statement. If a context has no jurisdiction over a statement, then the statement should not be interpreted in that context[7].
- A context may include an explicit description of the *semantic assumptions* it makes and the precise meaning of truth in that context. We call such a description the *institution* of the context.
- A context may be a *rich object* that has descriptions about its properties (such as provenance information) and relations to other contexts.

In order to fulfil these goals, we extend [McCarthy and Buvac, 1994] 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 the context of the statement α (i.e., α can be interpreted using the semantic assumptions made in the institution of c). Note that, 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:

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

[7]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.

An "isin" relation can be negated or quantified the 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 the use of the statement in the wrong context (i.e., we will be able to avoid a situation where the statement is "taken out of context").

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

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

where pl stands for the context of Propositional Logic.

Note that the Propositional Logic of Context (PLC) [Buvac and Mason, 1993], a logic based on the framework of [McCarthy and Buvac, 1994], 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.

C. Context Constructors and Axioms

Similar to lifting axioms in [McCarthy and Buvac, 1994], there are many useful relations between contexts that can be captured by *context constructors and axioms*.

Union. A union constructor "$\vee$", 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

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

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 to be 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

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

We always have that

$$c_1 \land c_2 \Rightarrow c_1 \text{ and } c_1 \Rightarrow c_1 \lor c_2$$

Note that c_1 may not necessarily inherit other properties of c_2, e.g., provenance-related properties.

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 the use of a statement out of context. For a context c, $\neg c$ stands for the union of all contexts that are incompatible with c. Thus, 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 also be incompatible with c_2:

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

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.

IV. Concrete Representation of Contexts

The foregoing discussion deliberately leaves out the design of a concrete syntax for context representation. Representation of some aspects of contexts may also be produced by the design of ontologies for the following:

- A standard vocabulary and ontology of context relations.
- A provenance model for contexts.
- A machine-understandable language for institution description, e.g., using RIF (a rule language) [Boley and Kifer, 2010].
- An investigation into how to use policy languages (e.g., AIR [Kagal et al., 2008]) to manage multiple applicable contexts of an ontology and to realize situation-aware context selection.

We recently proposed a syntax for extending RDF with a context representation mechanism [Bao et al., 2010a]. In this section, we propose that, when the knowledge representation language is RDF (or other languages built on top of RDF, e.g., OWL), we can use Named Graphs (NG) [Carroll et al., 2005] as a concrete syntax for context representation.

A. Syntax

A named graph is a pair $ng = (n, g)$ with n, a URI[8], the *name* of the graph, and g an RDF graph (i.e., a set of RDF triples). NG is well-suited as a concrete syntax for context representation when the knowledge representation language is RDF; i.e. where contexts are identified as graphs. For example, in the statement "Eric Cartman lives in South Park", we can say that "*sp*" is a context for the statement and represent both the statement and the context as RDF:

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

:sp rdf:label "A South Park Context"^^
    rdf:string .
:sp a :TelevisionSeries .
:sp context:semantics <http://www.w3.org/TR/
    rdf-mt/>
```

Here we assume the prefix `context:` stands for a URI that hosts a context ontology describing the basic relations and properties of context as we discussed in the previous section. The design of such an ontology is left as future work.

Note that a graph may "receive" triples defined in another graph. For instance, the graph "sp1" extends "sp", thus the triple in "sp1" is also in "sp" even if it is not explicitly given in "sp".

```
:sp1 {
    :Kenny :livesIn :SouthPark .
}
:sp1 context:extend :sp .
```

[8]There is a recent proposal to define a new type called "graph literal" for graph names(http://www.w3.org/2010/06/27-rdfn-meta-minutes.html).

B. Semantics

The semantics of the NG-based context representation extends the model-theoretic RDF Semantics [Hayes, 2004] and Named Graph [Carroll et al., 2005] in the following aspects:

- Informally, a triple is interpreted by a context only if the triple is in the graphs identifying the context or its extensions.
- Every graph C has its own local domain of discourse of I_C. All graphs that share the same context also share the same domain of discourse in their interpretations. On the other hand, graphs that are in different contexts will not share the same domain of discourse.
- RDF(S) vocabulary and axioms are interpreted locally in the associated contexts. For instance, the `rdf:type` relation in a context C will be satisfied by the semantic conditions[9]:

  $$\text{x is in } \mathrm{ICEXT}_C(\text{y}) \text{ if and only if } <\text{x,y}> \text{ is in } \mathrm{IEXT}_C(\mathrm{I}_C(\texttt{rdf:type}))$$

  where subscript $_C$ indicates that the corresponding mappings are only in the domain of discourse I_C.
- Relations between contexts establish semantic conditions between contexts. For instance, if C2 extends C1, then if a semantic condition holds in I_{C1}, it must also hold in I_{C2}. If C2 is incompatible with C1, then all semantics conditions in I_{C1} are ignored in I_{C2}.

When there is no context declaration for an RDF document, a default universal context is used which has a universal domain of discourse. The proposed semantics will be reduced to the usual RDF semantics for this case.

V. Context Modeling in CPM

Military planning is a complex problem-solving activity that is typically undertaken in a distributed, collaborative environment. Military planning depends on an ability to communicate a common understanding of commander's intent, objectives, resources, and constraints. In addition, decisions made at any level of the planning can be better communicated if the justification for planning options is communicated.

The Collaborative Planning Model (CPM) [Allen et al., 2008] is a semantically-enriched framework that was developed to support military planning by providing representations for various types of plan-related information, e.g., goals, constraints, assumptions, and so on. The CPM is also able to represent the rationale associated with decisions that are made while creating the plan.

The main objective of the CPM is to support the creation, communication and enactment of military coalition plans. A guiding principle underpinning the design of the CPM has been that collaborative planning, replanning and plan execution may all be seen as distributed, collaborative problem solving activities, and that variations on different planning doctrines are logically motivated by differences in the context in which the military planning occurs. Thus, much of the effort in designing the CPM has been in the area of collaboration patterns and how such patterns might be represented.

In the CPM, several key concepts that have been previously modeled using different solutions can be unified by the approach to context modeling outlined above. In particular, we are able to represent the following aspects of the CPM using our context model:

- *Rationale*. The rationale associated with planning decisions specifies the reason why planning were made. This is an important piece of information that forms part of the context for a plan. Rationale information may be represented as a "rationale context" and linked to the original plan. In particular, the named graph based syntax could simplify the representation of some complex rationale-related representations, which previously relied on an RDF reification strategy.
- *Provenance*. The provenance of a plan is information that indicates the temporal (when), spatial (where), agent (who), and casual (why) properties related to a plan. This information can be modeled using the provenance ontology proposed by our context framework.
- *Semantic Assumptions*. The correct understanding of plan representations relies on an ability to match the intended semantic assumptions (e.g., closed world assumption, unique name assumption, etc.) adopted by the designer of the plan with those adopted by the user of the plan. By formally representing these assumptions as institutions in the context model, the user will be better informed about the intended use of the plan.

VI. Related Work

Contexts have been extensively studied in AI and other fields. We can only discuss the most relevant work here due to space limitations. For surveys on contexts in AI, see [Brézillon, 1999a], [Brézillon, 1999b], [Akman, 2002], [Loyola, 2007], and for a survey on context representation for the Semantic Web pre-2004 see [Bontas, 2004]. We do not discuss context-aware mashups (e.g., [Brodt et al., 2008]) and context-aware middleware applications (e.g., [Arabnia et al., 2010]), which are often concerned about the provenance modeling aspect of contexts.

A. Contexts in AI

McCarthy-style Contexts: Our work extends McCarthy's work on context modeling [McCarthy, 1993], [McCarthy and Buvac, 1994] 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 the truth of a statement is often unknown or meaningless when it is applied in the wrong context.

Guha [Guha, 1991] has extended McCarthy's notion of context and applied it in the CYC system [Lenat, 1995]. Knowledge statements in CYC are divided into *microtheories*, which serve as the contexts of the statements. A microtheory, similar to contexts in [McCarthy and Buvac, 1994], is an object that has a name and can be organized in a microtheory

[9] Please refer [Hayes, 2004] for the definitions of ICEXT, IEXT and I.

hierarchy. Guha's approach shares the same limitations as McCarthy's when it is applied to the Semantic Web.

Buvac and others[10] applied McCarthy's framework in various logics, leading to the study of the Propositional Logic of Context (PLC) [Buvac and Mason, 1993], [Buvac et al., 1994] and the Quantificational Logic of Context [Buvac, 1996], [Makarios, 2006]. 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 [Buvac et al., 1995] showed that 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 [Giunchiglia and Giunchiglia, 1992] are a family of logics based on two principles:

- Locality - Only partial knowledge is available and this part is called the context of 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 [Ghidini and Giunchiglia, 2001], 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 [Ghidini and Serafini, 1998] and Distributed Description Logics (DDL) [Borgida and Serafini, 2003], with the latter having a close relation to Semantic Web applications.

Bouquet and Serafini [Bouquet and Serafini, 2003], [Serafini and Bouquet, 2004] have compared multicontext logics and McCarthy-style contexts and have shown that lifting axioms are special forms of bridge rules in MCS. They also showed that, in general, McCarthy-style contexts are less expressive than multicontext logics.

While the application of multicontext logics in the Semantic Web is conceptually straightforward, there are some practical issues associated with the specification of compatibility relations between contexts. Two well-known problems are that knowledge cannot be transitively reused in DDL and bridge rules offer only limited expressivities to relate ontologies [Bao et al., 2006].

B. Context Modeling for the Semantic Web

Guha and others [Guha et al., 2004] applied McCarthy-style contexts for use on the Semantic Web, targeting the aggregation of independently published data. Their proposal shares some common properties with our framework, such that each document has a context which can be identified by an IRI/URL. Guha et al's work provides a small ontology to describe contexts, and an alternative approach to provide an extended RDF model theory for introducing contexts.

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

Stoermer[Stoermer, 2006], [Stoermer et al., 2007] also applied McCarthy-style contexts for RDF context management. For this purpose, the work introduced a Context Relations Ontology (CRO) without adding new language features to RDF (which is different from the approach adopted by [Guha et al., 2004])

Since both [Guha et al., 2004] and [Stoermer, 2006], [Stoermer et al., 2007] use an approach based on the ist relation, inherent limitations of the McCarthy-style contexts are also present in proposals by Stoermer.

C-OWL [Bouquet et al., 2003] is an extension of OWL, and it is based on Distributed Description Logics. The expressivity of C-OWL is limited to its use as an ontology mapping language. For example, an "into" bridge rule can be used to establish subclass-like relationships between classes in two ontologies. In addition, since a context is not an object in C-OWL, one cannot assert provenance or other properties about a context.

VII. Conclusions

In this paper, we proposed that context is important for the effective use of information content in distributed network environments. In particular, we proposed that an explicit representation of context information may be important in terms of enabling online information content to effectively support cognitive processing at both the individual and collective (social) levels (see [Huynh et al., 2010]). We identified several important aspects of context and proposed a generic context representation model. Our focus was on developing a formal model of contexts for the unambiguous and effective delivery of data and knowledge, and, in particular, for enabling automated inference that addresses contextual differences between physically distributed agents. We showed that this framework can be applied to the CPM to support the explicit representation of context-related information in military coalition plans.

Our future work will include the following:

- A formal semantics for the context formalism and a natural deduction system for the framework.
- A detailed named graph based concrete syntax for expressing contexts that can work with RDF and OWL, as well as a vocabulary of basic context relations.
- An investigation into the use of the context framework to support the representation of plan-relevant information using the CPM.

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