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Inconsistency Handling in Collaborative Knowledge Management

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***Abstract*—One of the challenges of knowledge management is handling inconsistency. Traditionally, it was often perceived as indication of invalid data or behavior and as such should be avoided or eliminated. However, there are also numerous situations where inconsistency is a natural phenomena or carry useful information. In order to decide how to manage inconsistent knowledge, it is thus important to recognize its origin, aspect and influence on the behavior of the system. In this paper, we analyze a case of collaborative knowledge management with hybrid knowledge representation. This serves as a starting point for a discussion about various types of inconsistencies and approaches to handle it. We analyze sources, interpretation and possible approaches to identified types of inconsistencies. We discuss practical use cases to illustrate selected approaches.**

I. Introduction

INCONSISTENCY, defined in various sources as inability for all conceived statements or beliefs to be simultaneously true, is a major issue in knowledge management (KM). Contradiction, often used as a synonym, is an especially strong kind of inconsistency between sentences such that one sentence must be true and the other must be false [1].

Inconsistency management has found application in various areas including: knowlege-based systems analysis [2], [3] and verification [4], multiagent systems, information retrieval, recommender systems, and intelligent tutoring systems [5].

While inconsistency of data is usually undesirable, inconsistency of knowledge constitutes a more complex challenge [6]. Firstly, it is not always easy to discover, because it may appear on different levels of knowledge representation and reasoning. Secondly, in distributed and dynamic environments, it may be a natural phenomena that carry useful information.

There exist various approaches to handle inconsistency [7], [8], from elimination, through consensus methods [5], [9] and argumentation frameworks [10], [11], up to paraconsistent reasoning tolerating inconsistent information [12]. Sometimes it is useful to first measure the inconsistency [13], [14] and based on the results decide what to do with it [15], [16].

In our research, we analyze inconsistency in a collaborative knowledge management environment (see Fig. 1). With the rapid development of new technologies, collaborative environments for knowledge management become increasingly complex. Knowledge in such environments is represented with use of diversified formal, semi-formal and informal methods [18].

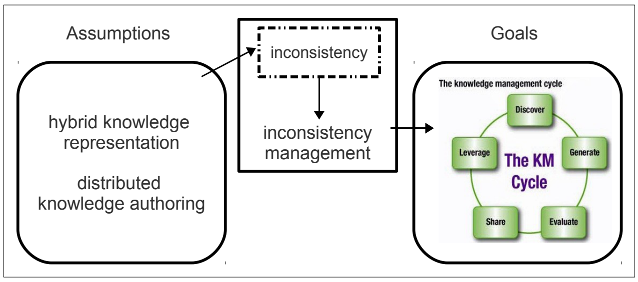

Figure 1. Inconsistency in Collaborative Knowledge Management (the knowledge management cycle as in [17]).

In this work, we concentrate on knowledge representation with Semantic Web technologies. Within this area, we investigate:

- Challenges and problems related to inconsistency,
- Sources of inconsistency, and
- Approaches to handle inconsistency.

This paper is organized as follows: Motivation for our research is given in Section II. Theoretical background of handling inconsistency is outlined in Section III. Selected problems and approaches to handle inconsistency on the Semantic Web are then discussed in Section IV. In Section V, an analysis of the approaches with respect to knowledge management is given. Use case scenarios are presented in Section VI. The paper is concluded in Section VII.

II. Motivation

Motivation for research presented in this work stems from the experiences of BIMLOQ[1] and INDECT [19], [20] research projects. The former was focused on quality of knowledge represented with business processes, rules and semantics. Within the latter a collaborative knowledge management environment was developed that used semantic technologies and social features to foster collaboration. The projects revealed the importance of practical challenges of inconsistency in knowledge management, related specifically to:

1) Dynamics of the system (integration, revision, merge),
2) Distributed knowledge authoring, and
3) Different methods of knowledge representation.

[1] See http://bimloq.ia.agh.edu.pl.

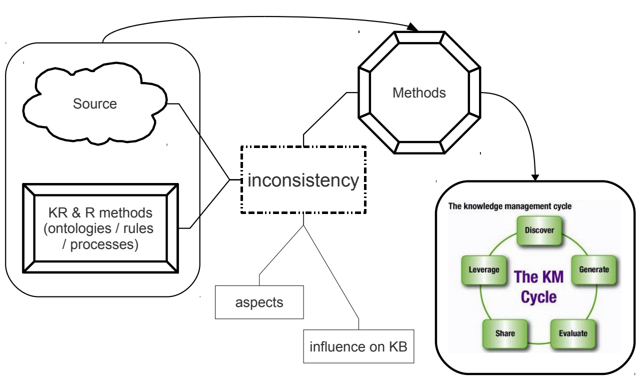

Figure 2. Map of areas for inconsistency analysis.

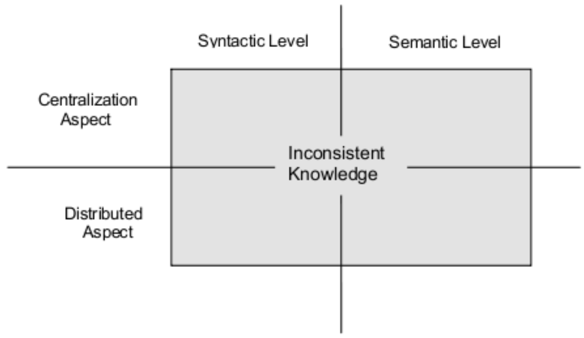

Figure 3. Aspects and levels of inconsistency [29].

Therefore, when considering a collaborative knowledge management environment with hybrid knowledge representation we aim to analyze (see Fig. 2):

1) How knowledge representation influence inconsistency?
2) What are the sources of inconsistency in selected areas?
3) What are possible approaches to handle it?

Our basic testing platform is a semantic knowledge-based wiki that supports semantic technologies and rule-based reasoning [21]. Semantic wikis proved to be useful in collaborative knowledge management and engineering [22]. They constitute a flexible tool for knowledge representation and reasoning [23], as well as distributed knowledge acquisition [24]. Our implementation supports semantic technologies and rule-based reasoning. Combining different method of knowledge representation within a semantic wiki have been proposed by authors in several works: business processes with rules [25], and rules with semantics [26], [27]. There are ongoing works on integrating semantics with business processes [28].

Currently, the system (available at http://loki.ia.agh.edu.pl) is not equipped with any mechanisms for handling inconsistencies. Ultimately, we aim to develop a system that will allow for knowledge representation with semantic technologies, rules and business processes, able to deal with inconsistency.

We claim that in such an environment handling inconsistency is a complex challenge and one should consider methods that *accept* it rather than eliminate. In the following section, we briefly review selected concepts, approaches and theoretical bases for the problem of inconsistency. This is the starting point for more detailed and focused review given in Section IV. In this paper, we analyze the case of the Semantic Web technologies and present selected approaches to deal with inconsistent knowledge.

III. Theoretical Foundations

A. Vocabulary related to Inconsistency

When talking about *inconsistency*, one can find several definitions and interpretations of the core terms used in the area. Here we assume the following definitions:

- Inconsistency – when set of sentences or beliefs cannot be true at the same time or under the same interpretation
- Contradiction – when having two sentences or beliefs if one is true, then the other cannot be true,
- Paraconsistency – way of amending classical logic to be able to reason (conclude meaningful statements) in presence of inconsistency (ECQ does not hold).

B. Aspects and Levels of Inconsistency

One can consider different aspects and levels of inconsistency (see Fig. 3). In *distribution aspect*, basic cause of inconsistency is the independence of knowledge agents or knowledge processing mechanisms, while in *centralization aspect* inconsistency is related to dynamic changes of a world.

Inconsistency can be identified and processed on a *syntactic* and *semantic* level [29]. Analogously, inconsistency can be checked for in a purely *logical* way (e.g. p and $\neg p$ are present in the knowledge under discourse), or as *material* inconsistency, when two pieces of knowledge are invalid together due to the assumed interpretation [30].

Taking into consideration possible actions in the presence of inconsistency, one may take a *actual-contradictions* view or *potential-contradictions* view [7]. The former assumes that contradictions can appear in a knowledge base and no ”degenerate” reasoning should occur when contradictory statements are jointly asserted. Every statement should be treated equally. However there are two main approaches: First is that contradictions are ”bad”: if they appear, then reasoning collapses and results are trivial. The other is that the contradictions arise naturally and can be more informative than any consistent revision of the theory. Potential-contradictions view claims that contradictions do not actually exist, so there are either some statements ”responsible” for the inconsistency or the contradictions can be resolved by using argumentation. Concrete realization of potential condradictions view is in defeasible reasoning.

C. Formal Representation of Inconsistency

In order to formalize inconsistency handling in logic, there must be a formal representation of inconsistency itself. In [7], where logics are defined as ”formal systems consisting of a language L (in the form of a set of formulas) on which an inference operation C is defined." three approaches to represent inconsistency are distinguished:

- *C-scheme*: to relate contradictions to inference, stating that inconsistency arises when all formulas are inferred,
- *A-scheme*: to pick a subset of the language, and use each element of the subset as a representation of absurdity, and
- *N-scheme*: contradictions are captured through an auxiliary notion of negation ($A, \neg A$ or $A \wedge \neg A$ if conjunction is available, is a syntactical account for inconsistency).

Inconsistency may be also represented in a form of *conflict profiles* as explained in [5]. Finally, contradictions can be *incorporated* into the formal logic by augmenting the classical logic. One of the most successful is Belnap's 4-valued logic [31] in which we can represent a statement that can be inferred to be true and false at the same time. This logic has been successfully used in the context of DL ontologies as will be shown in Section IV-B.

IV. Inconsistency on the Semantic Web

Semantic technologies are used to represent and process data, information and knowledge on several abstraction levels. Relations between objects are described with RDF [32] and simple classification can be done in RDFS [33]. Ontologies constitute the main method of knowledge representation. Integration with rules as well as incorporation of them within ontologies is an active research area. Inconsistency can be therefore considered on various levels as presented in the following subsections.

A. Inconsistency in RDF/S

RDF allows to describe objects by means of statements about their attributes and relations to other objects. The statements build a graph representing positive knowledge about the conceived world. In order to ascribe a category and build simple taxonomies, RDF Schema was introduced. It supports basic relation that define the *type* of an object, *domain* and *range* of certain relations etc. Reasoning in RDF/S is based on their defined semantics and set of entailment rules.

In order to avoid inconsistency, it was not allowed to use explicit negation in RDF/S. Open World Assumption that traditionally holds on the Semantic Web means that if something is not stated, it does not mean that it is not true. However, despite this restriction, there still exist inconsistent RDFS statements, e.g., ones that violate domain/range restrictions.

To deal with inconsistency, Extended RDF (ERDF) [34] has been proposed. Its semantics is based on *partial logic* that allows to express both *strong* and *weak* negation and can support reasoning with Closed-World Assumption as well as Open-World Assumption (this can be set by author of a semantic knowledge base). Stable model semantics of Extended RDF (ERDF) ontologies has also been proposed.

The approach is realized in MWeb framework[2]. The tool uses *restricted propagation of local inconsistencies*, making it possible to reasoning even in the presence of an inconsistency, local to a Web rule base and reasoning mode.

[2] See http://centria.di.fct.unl.pt/~cd/mweb/.

B. Inconsistent Ontologies

Formal ontologies, understood as logical theories, should typically be consistent. However, there are different situations where inconsistency may appear.

1) Problems and Sources of Inconsistency: Several problems related to inconsistent ontologies are distinguished [35]: ontology mismatch and conflict, ontology merging, and integration. Two former are related to specific relations between two or more ontologies. Two latter refer to some activities performed on ontologies. Main scenarios for a formation of inconsistency are given in [36]:

- *Multiple sources*, for example if the ontology is built by several authors, or during such processes as merging, integrating and aligning ontologies.
- *Mis-representation of defaults*, for instance if a more general concept is inconsistent with more specific facts.
- *Moving from other formalism*, for example if in the target formalism there are restrictions that make the translated information contradictory.
- *Polysemy*, if the same name refers to different concepts with inconsistent definitions.

2) Inconsistency Levels: Differences between ontologies may appear on various levels. While instances can be identified on the physical level (referring to their being in the real world), concepts are identified only on the logical one, that is referring to their names and structures. Nguyen [35] distinguishes the following levels of inconsistency between ontologies (called *ontology conflicts*):

- *Inconsistency on the instance level*: the same instance belonging to different ontologies does not satisfy the instance integration condition which states that if the instance is described differently in different concepts then in referring to the same attributes they should have the same value.
- *Inconsistency on the concept level*: There are several concepts with the same name having different structures in different ontologies.
- *Inconsistency on the relation level*: Between the same two concepts there are inconsistent relations in different ontologies.

3) Selected Approaches to Handle Inconsistency: Several approaches to inconsistency have been adapted for ontologies. On the one hand, inconsistency in ontologies can be diagnosed and repaired before reasoning [37] (including forgetting-based approach [38]). On the other, one can use conflicts to generate new knowledge or perform meaningful reasoning over inconsistent ontologies. Sometimes, it is not practical or even possible to resolve inconsistency (due to the access restrictions or possible information loss). The following examples illustrate selected approaches that seems especially suitable for collaborative knowledge management:

a) Consensus-based methods: Consensus-based methods have been discussed in [35] as a way to resolve inconsistency during ontology integration. Algorithms to determine a consensus on the instance, concept and relation level have been proposed. For a set of different versions of data (so called *conflict profile*) they determine such a version that best represents the given versions.

b) Argumentative frameworks: Argumentative framework for reasoning with inconsistent DL ontologies has been proposed in [10], [11]. The proposal involves expressing DL ontologies as Defeasible Logic Programs (DeLP). Once a query is posed to an inconsistent ontology, a dialectical analysis on a DeLP program (obtained from such ontology) is performed and all arguments in favor and against the final answer of the query are taken into account [10].

c) Selecting consistent subsets: This approach, introduced in [36] and extended in [39] is based on selecting consistent sub-theories from inconsistent ontologies using selection functions based on syntactic [36] or semantic [39] relevance. Reasoning is then executed on the consistent subset and if a satisfying answer cannot be found, the sub-theory is appropriately extended. In [40], minimal inconsistent sets (MIS) and a resolution method are proposed to improve the run-time performance of the inconsistency reasoner. The approaches have been implemented in PION (Processing Inconsistency ONtologies) tool within the LarKC project.[3]

d) Paraconsistent reasoning: One can also extend the classical logic for OWL (Description Logics are subsets of First Order Logic) to many-valued paraconsistent logic. A proposal of representing inconsistent ontologies with 4-valued logic has been proposed in [41], [42]. In this approach, two additional truth values, namely *underdefined* and *overdefined* (i.e. contradictory) are used. Thanks to the mapping between the logics, it is possible to use classical OWL reasoners to operate on inconsistent knowledge. This idea has been implemented in RaDON NeoN Toolkit Plugin.

V. Analysis and Discussion

Traditionally, in analysis and verification of knowledge-based systems, inconsistency was undesirable and negatively influenced the quality of a knowledge. With the advent of modern Web-based environments, collaborative knowledge management becomes vital. Inconsistency in such environments seems unavoidable. It can be considered in distribution and centralization aspect, i.e., related to the multiple sources or dynamic changes over time. Inconsistency may be discovered during a process of knowledge integration, e.g. ontology aligning or merging, or observed in a static knowledge base, e.g., a fact base may contain inconsistent statements.

Even within the narrowed field of knowledge representation with Semantic Web technologies, there exist various approaches to handle inconsistency that partially depend on the representation level. In case of RDF/S, the knowledge base consists of positive statements, assertions with limited semantics. Inconsistency here is closely linked to the issue of negation. ERDF aims to solve this problem by introducing strong and weak negation into the language and allowing the knowledge engineer to state whether Closed- or Open-World Assumption should be adopted. OWL Ontologies are logical theories based on formal logic. If classical semantics is adopted, then inconsistency make them unusable and thus should be suppressed, e.g., by consensus finding or repairing methods. However, if the semantics is re-defined, one can tolerate and represent inconsistent information e.g., by using one of paraconsistent logics.

Particular phases of knowledge management cycle [17], poses various challenges related to inconsistency, including:

- *Discover*: information fusion from multiple sources, independent experts, independent knowledge processing,
- *Generate*: various views or opinions expressed in mutually inconsistent concept descriptions, self-contradictions,
- *Evaluate*: measuring inconsistency, meaningful query answering and reasoning in inconsistent knowledge bases,
- *Share*: merging, aligning, integrating knowledge,
- *Leverage*: searching for a consensus or argumentation.

Circumstances in which inconsistency appears and the level of knowledge representation it affects may have a deciding influence on the method one will choose to manage the inconsistency. Selected approaches, presented in this paper and summarized in Table I, illustrate various aspects and scenarios that may be adapted in collaborative knowledge management.

VI. Use Case Examples

In this section, we present selected use cases of handling inconsistency in collaborative knowledge management. Let us consider a semantic wiki with underlying logical knowledge representation that supports semantic technologies, rule-based reasoning and business process modeling [21], [23], [28].

A. Collaborative Ontology Development

In this case, autonomous experts jointly model a single knowledge base (e.g. an ontology). During the process, the ontology becomes inconsistent.

1) Case: Inconsistency on relation/concept/instance level.

2) Source of the Inconsistency: Distributed authoring.

3) Interpretation of the Inconsistency: Authors may have different opinions or diversified knowledge about the subject.

4) Suggested Approach: If classical semantics is adopted, consistency should be regained. Consensus methods (taking into account different opinions) or argumentation framework (identifying the best option) could be used to resolve conflicts.

B. Collaborative Recommendation System

In this case, autonomous knowledge agents independently assert their opinions and ratings about movies in the system.

1) Case: Pieces of knowledge (facts) are inconsistent.

2) Source of the Inconsistency: Distributed authoring / Dynamic updates.

3) Interpretation of the Inconsistency: Authors may have different opinions and there is no way to arbitrarily say which one is good and which one should be eliminated. / Authors add, remove or change their opinions over time.

4) Suggested Approach: Inconsistency should be accepted (all opinions should be represented, regardless of contradictions). Paraconsistent reasoning, e.g. using four-valued logic could be used.

[3] See http://larkc.eu.

Table I
SELECTED APPROACHES TO INCONSISTENCY ON THE SEMANTIC WEB

Reference	Problem	Knowledge Representation	Approach	Tool
[10], [11]	ontology integration	DL	argumentative framework	–
[34]	reasoning with inconsistent information	RDF/S	stable model semantics, partial logic (strong and weak negation)	MWeb
[35]	ontology integration	not specified (solution on a general level)	determining consensus on instance/concept/relation level	–
[36], [39] [40]	querying inconsistent KB	DL	selecting consistent subsets	PION (plugin for LarKC tool)
[41], [42]	reasoning with inconsistent KB	$\mathcal{SROIQ}$ DL	mapping to 4-valued logic	NeoN Toolkit Plugin RaDON

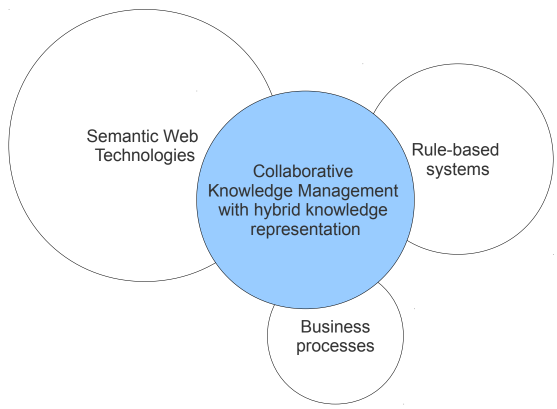

Figure 4. Inconsistency in Collaborative Knowledge Management.

VII. SUMMARY AND FUTURE WORK

Collaborative Knowledge Management poses numerous challenges related to inconsistency. It may result from the distributed authoring as well as dynamic changes of the world and the system. Inconsistency may be considered on a purely syntactic level or on a level where the semantics play a significant role. While in some situations inconsistency signals erratic data or behavior and should be resolved, sometimes it is natural or even useful. In order to apply appropriate technique to handle inconsistency, it is necessary to recognize and understand its origin and influence on the system. In this paper, we analyzed inconsistency in collaborative knowledge management. We presented selected problems of inconsistency and approaches to handle it.

In order to build a comprehensive collaborative environment with hybrid knowledge representation that is capable of handling various sorts of inconsistency, we consistently investigate each area of considered knowledge representation (see Fig. 4). In this paper, we have analyzed the area of Semantic Web taking into account various levels of knowledge representation and different situations in which inconsistency may arise.

In future, we plan to analyze inconsistency handling in rule-based systems [43], [44], business processes, and Multi-Context Systems [45]. Quality of knowledge will also be addressed, taking into consideration Information Quality criteria.

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