A New Framework for Systematic Analysis and Classification of Inconsistencies in Multi-Viewpoint Ontologies

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Zhitomirsky-Geffet, Maayan and Golan Avidan. 2021. "A New Framework for Systematic Analysis And Classification of Inconsistencies in Multi-Viewpoint Ontologies." *Knowledge Organization* 48(5): 331-344. 36 references. DOI:10.5771/0943-7444-2021-5-331.

Abstract: Plurality of beliefs and theories in different knowledge domains calls for modelling multi-viewpoint ontologies and knowledge organization systems (KOS). A generic theoretical approach recently proposed for heterogeneity representation in KOS was linking each ontological statement to a specific validity scope to determine a set of conditions under which the statement is valid. However, the practical applicability of this approach has yet to be empirically assessed. In addition, there is still a need to investigate the types of inconsistencies that might arise in multi-viewpoint ontologies as well as their possible causes. This study proposes a new framework for systematic analysis and classification of inconsistencies in multi-viewpoint ontologies. The framework is based on eight generic logical structures of ontological statements. To test the validity of the proposed framework, two ontologies from different knowledge domains were examined. We found that only three of the eight structures led to inconsistencies in both ontologies, while the other two structures were always present in logically consistent statements. The study has practical implications for building diversified and personalized knowledge systems.

Received: 7 June 2020; Revised: 21 September 2020; Accepted: 13 April 2021

Keywords: ontology building, reasoning, relationships, domain analysis

1.0 Introduction

In computer and information sciences ontologies are defined as formal specifications of terms and the relationships between them in a specific domain (Gruber 1993). Ontologies contain the main concepts of the knowledge domain, *classes*, semantic relationships between these classes, *properties*, restrictions on the properties and instances of the classes (Gandon 2010; Noy and McGuinness 2001).

Ontologies allow the formal organization of knowledge in a particular field, for sharing, retrieval, and analytic purposes both by humans and by smart automatic agents. Smart agents use ontology as a common formal language to provide various automated services, such as answering complex questions by crossing and analyzing large amounts of data from diverse sources and thereby saving manual work.

In different areas there are different, and sometimes contradictory, opinions that ontology builders may want to include in the ontology. Therefore, building a consistent ontology is a challenge, as in many domains, such as medicine, nutrition, history, politics and even exact sciences, it is often difficult for experts to reach a consensus. For example, in the field of nutrition, there are studies that encourage the consumption of dairy products, while other research opposes it. Such contradictions between statements are considered an obstacle for automated agents that use the resulting ontology.

Creating ontologies in fields based on theories, rather than empirical results, such as math and physics can also be problematic. Claims, theorems, or axioms from one theory can contradict another theory's claim. Therefore, the ontology builders in these fields, also need to find a way to express the plethora of theories exhaustively, logically, and consistently.

Several types of inconsistencies and heterogeneities in ontologies have been addressed in previous research (Euzenat and Shvaiko 2013), such as syntactic, terminological, structural, and conceptual. Syntactic heterogeneity refers to two ontologies encoded in different formal schemes or standards. This can be solved by transforming the syntax from one standard to another. Terminological heterogeneity can be resolved by utilizing synonym recognition or thesauri. Structural inconsistencies, caused by different levels of granularity of the taxonomic structure of the ontologies, can be resolved using graph merging based methods (Mahfoudh, Forestier and Hassenforder 2016).

The last category, namely the conceptual heterogeneity, represents semantic and logical inconsistencies, and its causes are still underexplored in the literature. Hence, the objective of the current research is to determine which kinds of logical semantic inconsistencies can occur in multi-viewpoint and multi-theory ontologies for a specified knowledge domain, and how they can be resolved in a unified consistent model. To this end, we propose a generic framework for systematic analysis and classification of multi-viewpoint ontologies. The framework is based on eight generic logical structures that exist among pairs of ontological statements of the form "subject – relationship – object". The structures are based on the interpretation of classes and relationships as sets in the description logic, and analyzing the relations between those sets. The framework also assists in understanding the logical and ontological causes of the detected inconsistencies. An additional goal of the study was to utilize the framework to assess the applicability of the recently proposed theoretical model for inconsistency resolution in multi-viewpoint ontologies (Zhitomirsky-Geffet 2019). The main principles of Zhitomirsky-Geffet's model are a statement-based (rather than element-based) approach, attaching validity scopes to all the statements in the ontology and ensuring that inconsistent statements are valid in distinct validity scopes.

To this end, two ontologies were examined in the fields of:

1. Nutrition and its effect on the human health. This ontology was constructed based on the scientific literature in the field of nutrition as part of an experiment with 16 graduate students from the Information Science Department at Bar-Ilan University (Zhitomirsky-Geffet, Erez, and Bar-Ilan 2017);
2. Euclidean and non-Euclidean geometries. This ontology was built by a domain expert and 13 students of Achva Academic College in Israel majoring in high school mathematics education.

The ontologies represent two types of scientific knowledge. The first is empirical, based on clinical experiments and their results. The second is theoretical, based on axioms, theorems, and logical relations between them. Those two domains of knowledge were chosen in order to examine whether there are different types of inconsistencies in the empirical domain as opposed to the theoretical one, and vice versa.

The following research questions were addressed in this study:

1. Which kind of conceptual inconsistencies might exist, given ontologies that represent different viewpoints or theories in a certain domain?
2. Do different kinds of inconsistencies exist in different domains?
3. What are the causes of these inconsistencies, and how can they be resolved in a unified ontological model?

2.0 Related literature

2.1 Ontological inconsistencies in multi-viewpoint environment

Since each ontology is created by different experts and bodies, there might be many differences between the ontologies in the same domain of knowledge. Ontological inconsistencies for a given domain affects their reusability (Fernández-López et al. 2019). Therefore, in the past, several frameworks have been proposed for collaborative ontology construction and integration (Pereira 2008; Euzenat and Shvaiko 2013; Shvaiko and Euzenat 2013; Simperl and Luczak-Rösch 2014). Today, it is generally acknowledged that ontologies should be developed and maintained in a community-driven manner (Simperl and Luczak-Rösch 2014; Muresan and Klavans 2013), with tools providing collaboration platforms, enabling ontology stakeholders to exchange ideas and discuss modeling decisions. The most crucial phase in the collaborative process is reaching a consensus between the participants on the resulting ontology.

In scientific domains, diversity and controversy of knowledge is embraced as an essential feature of the scientific activity in which knowledge is produced (Tseitlin and Galili 2005). Weinberg (Weinberg 2001, 92), one of the prominent contemporary physicists, addressed this issue: "We [scientists] believe in the objective truth that can be known, and at the same time we are always willing to reconsider, as we may be forced to, what we have previously accepted". According to Hjørland's (2009) "theory theory" all concepts are grounded in theories and therefore cannot be understood across groups with different theories and beliefs.

According to researchers Zhitomirsky-Geffet and Bar-Ilan (2014), contradictions should be modeled at the ontological statements level (triplets of the form: class A – property – class B) rather than individual elements (classes or properties), because the logical and conceptual discrepancies between ontologies can be expressed at the statements level, even more than at the individual elements level.

Different fields of knowledge sometimes contain statements that cannot logically co-exist in the same knowledge model. Past research on the logics of inconsistencies deals with two main types of relationships that can exist between the two statements: contradictions and contraries. The first is a logical contradiction when the two given statements cannot be true or false at the same time (Horn and Wansing 2017). For example: *a patient is dead* and *a patient is alive*. In this case, the two opposite concepts are collectively exhaustive and there is no third or intermediate state (a patient who is not alive or dead), so if the first statement is true, the second is necessarily false, and vice versa.

Such contradictions can be drawn from the transitivity unification violation structure mentioned by Zhitomirsky-Geffet and Bar-Ilan (2014), when in one ontology a class A is a (direct or indirect) subclass of B, while in another ontology B is a (direct or indirect) subclass of A (and hyponymy is the only semantic relationship between these two classes). Other transitive semantic relationships such as "part-of" might produce a similar type of contradiction as well. For instance, *Music is part of Art* vs. *Art is part of Music*.

The second type of inconsistencies is contraries which are present for pairs of statements in which both cannot be true, but both can be false (Horn and Wansing 2017). For example, both statements: *dairy products increase the cholesterol level* and *dairy products decrease the cholesterol level* can be false, if a study has found no influence of dairy products on the level of cholesterol. This type of inconsistencies is included in the entailment unification violation structure provided by Zhitomirsky-Geffet and Bar-Ilan (2014), when one of the classes or instances in the first statement is an antonym of the corresponding class or instance in the second statement, e.g. *Social protest causes economic prosperity* vs. *Social protest causes economic crisis* or when both corresponding classes/instances in the two statements are semantically equivalent but their semantic relationships are antonyms, e.g. *Prime Minister supports social protest* vs. *Prime Minister attacks social protest*. These cases present a contrary (and not a contradiction) since there is a third option when both above statements are false due to the fact, that social protest has no effect on the economy and the Prime Minister does not relate to social protest at all.

Another case of contrary is when two statements do not necessarily contradict each other, but when the probability of the events they depict increases, they cannot co-exist in the same context (Hashimoto et al. 2012). For instance, *Dairy products might increase cholesterol levels* vs. *Dairy products might decrease cholesterol levels*. The statements can co-exist, when their joint probability is less than 100%. But if we replace "might increase" in the first statement to "increase", its probability becomes 100%, which makes it impossible for the two statements to be true simultaneously.

This study aims to refine and extend the previous research on ontological inconsistencies' classification and in particular to determine the reasons for inconsistencies in multi-viewpoint and multi-theory ontologies.

2.2. Causes of conceptual ontological inconsistencies

Several causes of conceptual ontological inconsistencies have been discussed in previous research. The first cause is the different opinions and beliefs of the ontologies' composers (Stead and Doerr 2015). The authors propose an extension to the generic CIDOC-CRM ontology, namely CIDOC-CRMinf, which explicitly designates various beliefs and their holders (Stead, Whitson-Cloud and Oldman 2014). Their model enables logical inference based on probabilities and fuzzy logic where each proposition might be assigned various types, i.e., more than two, of belief's truth values. Niccolucci and Hermon (2017) suggested another extension to CIDOC-CRM that allows an uncertainty to be modelled in the ontology using fuzzy logic. To this end, they present a reliability coefficient of ontological statements in the range of 0 and 1.

Other studies generalize the belief-based approach and argue that the inconsistencies are caused by differences between the local (true only for a single viewpoint) or global (true for more than one viewpoint) ontological elements (Hemam, Djezzar and Djoud 2016; Djakhdajkha, Hemam and Boufaida 2014; Djakhdjakha, Hemam and Boufaida 2012; Gnoli and Szostak 2014; Szostak 2014; Tennis 2016).

Several studies attribute the conceptual discrepancy in ontologies to their applicability in different contexts and situations (Baclawski, Kokar and Matheus 2003; Kokar, Matheus, and Baclawski 2009). They proposed a STO (Situation Theory Ontology). For example, the same medical procedure might save a person's life, while in another situation it might endanger his life and even be fatal. Similarly, a model of Context Slices was proposed by Welty (2010) and extended by Giménez-García, Zimmermann and Maret (2017) as the NdFluents model to explain the possible causes of ontological inconsistencies. This model creates different context-dependent ontological classes for various contexts. For example, to define that *Paris is the capital of France*, the model defines classes Paris@1 and France@1 as temporal parts of Paris and France correspondingly, which exist only in a certain time period (since 508). Contexts can be temporal, geographic, or situational.

The above causes of inconsistencies have been unified and generalized by Zhitomirsky-Geffet (2019) who defined a generic model for inconsistencies in ontological knowledge conceptualization, where each ontological statement has an epistemological component, the validity scope type, a set of conditions under which the statement is valid, which includes viewpoints and beliefs, contexts and situations, experimental settings and population types. According to this model, inconsistencies are caused by ontological statements that cannot be both valid in the same validity scope. They can therefore be resolved by identifying and assigning each of these statements to a different validity scope. The main steps in the construction process of the open knowledge organization network (Zhitomirsky-Geffet 2019) are as follows:

1) Every statement is associated with the type of the validity scope from the validity scope ontology that makes it valid.
2) All the statements that are valid in the same validity scope are grouped together into a separate subsystem. At this point, statements which are valid in multiple validity scope types represent universal knowledge and are thus included in all the groups associated with each of these validity scope types.
3) These universal statements are then moved into a separate *linking* subsystem that is connected with all the subsystems that share a validity scope type with them.

The network of multi-viewpoint ontological subsystems (denoted S1, S2, etc.) is depicted on the left side of the diagram in Figure 1 and the ontology of the validity scope types (V1, V2, etc.) is on the right. The blue edges represent the links between the ontological subsystems in the network and also the internal taxonomic relationships between the validity scope types in the validity scope ontology, while the orange edges link the subsystems with the validity scopes in which they are valid. For example, S2 is valid only in V6, and S3 is valid only in V7, while the linking subsystem S1 is valid in both V6 and V7 and therefore is linked to their superclass V5.

Statements are clustered by their association with various validity scope types into internally coherent subsystems. Each of the subsystems is associated with a validity scope type. These subsystems form a knowledge organization network connected through the universal (consensual) subsystems with more than one validity scope type (Zhitomirsky-Geffet 2019). As a result, a network of inter-connected knowledge organization subsystems is created. The competing viewpoints and theories (subsystems) are easily identified in the constructed network, as they are associated with the subclasses of the same validity scope type (e.g., "plane" and "sphere" are both subclasses of the validity scope type "geometrical space", and each might serve as a validity scope type for a knowledge representation system of a different theory in Geometry). In this study, we adopt the unified ontological model and the concept of the validity scope in order to resolve the detected inconsistencies.

3. Methodology

3.1 A generic framework for classification of inconsistencies among ontological statements

We propose a method that will examine which types of inconsistencies can exist between statements and what causes these inconsistencies both at the ontological and the episte-

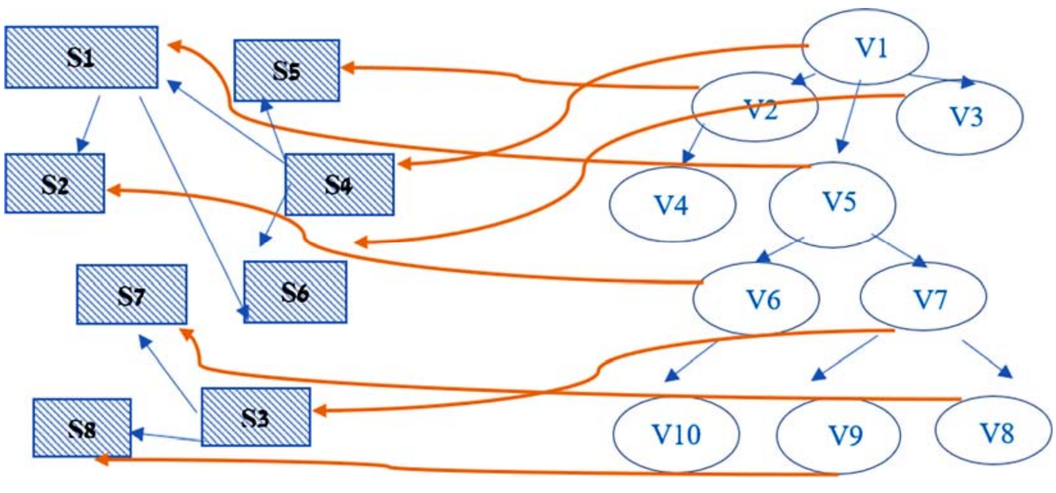


Figure 1. A schematic global view of the open knowledge organization network model.

mological levels. The method defines all possible logical structures of the relations between a pair of ontological statements. The ontological statement is a triplet of the following form: subject – property – object, where subject and object are two classes and the property is the semantic relationship between them. Each class in an ontology is a set of specific instances and each relationship is a Cartesian product of the instances' sets of the two classes (a set of pairs of instances) (Baader and Nutt 2010).

We define the following types of relationships between the corresponding elements in two different statements (i.e. the subject of statement A vs. the subject of statement B, the relationship in statement A vs. the relationship in statement B and the object in statement A vs. the object in statement B):

1. Identity: the two corresponding elements in two ontological statements are identical.
2. Equivalence (further denoted as $A \equiv C$): the two ontological elements possess the same semantic meaning but different names (such as synonyms, scientific names in contrast to layman's terms, etc.).
3. Inclusion: all instances of the ontological class A in the first statement are included in the corresponding class B of the second ontological statement. The inclusion stems from the taxonomic relationship among classes that exists in each ontology. For semantic relationships, inclusion holds if all the pairs of instances of the first statement's relationship are included in the set of pairs of the relationship of the second statement.
4. Disjointness (further denoted as $A \cap B = \emptyset$): the two corresponding classes do not have common instances. In this category there are two different sub-cases:
   - When two corresponding classes or relationships are semantic antonyms, and given that the remaining elements in the two statements are identical or equivalent, respectively, the two statements are inconsistent and cannot coexist simultaneously in the same validity scope.
   - When the two classes or relationships are ontologically disjoint but are not semantic antonyms, and given that the remaining elements in the two statements are identical or equivalent, respectively, the statements are not inconsistent and can coexist simultaneously in the same validity scope.
5. Partial overlap – there are common instances and non-common instances for the two classes, or there are common and non-common pairs of instances in the sets of two relationships.

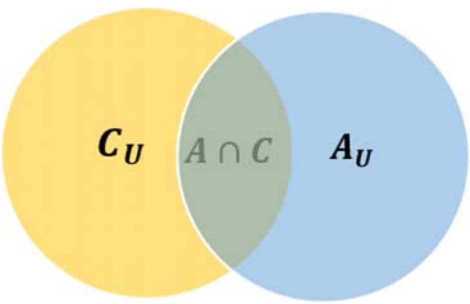
It is noteworthy that in ontologies there is no distinction between relations of identity and equivalence since one class or property is always chosen to represent all the synonyms of the corresponding semantic meaning. Thus, there are four possible relationship types among pairs of elements in two ontological statements.

Because all the statements are triples of the same form, in order to detect potential inconsistencies, one can compare the corresponding pairs of elements in the two statements. Hence, for two general statements:

$$\begin{cases} Vp1: A - R - B \\ Vp2: C - Q - D \end{cases}$$

we can examine each of the subcases stemming from the four possible relationships (described above) between A and C (4 types of relationships), combined with each of the 4 types of relationships between B and D and multiplied by four possible types of relationships between R and Q. This type of analysis leads to $4^3 = 64$ combinations of possible relationships between the two triples (statements). Consequently, this is too many cases to analyze, but as we will demonstrate below this number can be significantly reduced.

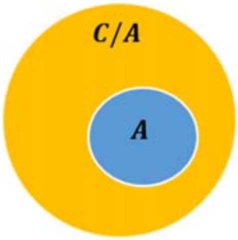
Note that cases of partial overlap and inclusion, between the classes (or the relationships) can be represented as equivalent and disjoint based on the instances in the intersection and the instances not in the intersection, respectively. For example, in the case in which A and C partially overlap (Figure 2) we can denote the instances unique for A as A_U and those unique for C as C_U and obtain the following pairs:



$$(1)\begin{cases} Vp1: A_U - R - B \\ Vp2: C_U - Q - D \end{cases}$$

$$(2)\begin{cases} Vp1: A \cap C - R - B \\ Vp2: A \cap C - Q - D \end{cases}$$

Figure 2. Partial overlap between two classes.



$$(1)\begin{cases} Vp1: A - R - B \\ Vp2: A - Q - D \end{cases}$$

$$(2)\begin{cases} Vp1: A - R - B \\ Vp2: C/A - Q - D \end{cases}$$

Figure 3. Inclusion between two classes.

Pair (1) is a pair of statements with two classes of subjects with the disjoint relationship between them and pair (2) has two classes of subjects with the equivalence relationship. Pair (1) and pair (2) can be analyzed separately as they do not add knowledge to one another because they do not contain common instances (by definition).

Similarly, the inclusion relationship between two ontological elements can be reduced to equivalence in the inconsistency analysis (Figure 3). If A is contained in C, we can create the following pairs of statements:

C/A is the class of instances in C but not in A (the difference between the two classes). In pair (1) the class of subjects is equivalent and in pair (2) the classes of subjects are disjoint. Assuming C's internal consistency, pair (2) should always be consistent and thus can be ignored in the statements' analysis.

In this manner we can represent pairs of statements in cases of partial overlap and inclusion for the relationships and for the classes of objects. Consequently, the possible relationship types that remain between ontological elements are equivalence or disjointness, leaving us with $2^3 = 8$ possibilities of relations between the statements. Table 1 presents the possible relations (logic structures) between the statements when R ≡ Q (R is equivalent to Q).

For $R \cap Q = \emptyset$ (R and Q are disjoint) we get the structures shown in Table 2.

In this study we applied the proposed framework for classifying inconsistencies on two multi-viewpoint ontologies constructed as described below.

3.2 The multi-viewpoint nutrition ontology

In the field of nutrition, the experiment was conducted as part of the research reported by Zhitomirsky-Geffet, Erez, and Bar-Ilan (2017) and as a result an ontology of 776 statements was constructed. In this study, 16 graduate students in the Department of Information Science were asked to construct an ontology that would reflect one of the nutrition approaches regarding meat, dairy, and soy products.

Structure *S1*	Structure *S2*
$A \equiv C, R \equiv Q, B \equiv D$	$A \equiv C, R \equiv Q, B \cap D = \emptyset$
Structure *S3*	Structure *S4*
$A \cap C = \emptyset, R \equiv Q, B \equiv D$	$A \cap C = \emptyset, R \equiv Q, B \cap D = \emptyset$

Table 1. Possible relational structures between the statements when R ≡ Q.

Structure S5	Structure S*6*
$A \equiv C, R \cap Q = \emptyset, B \equiv D$	$A \equiv C, R \cap Q = \emptyset, B \cap D = \emptyset$
Structure S*7*	Structure S*8*
$A \cap C = \emptyset, R \cap Q = \emptyset, B \equiv D$	$A \cap C = \emptyset, R \cap Q = \emptyset, B \cap D = \emptyset$

Table 2: Possible relational structures in statements when $R \cap Q = \emptyset$.

1. The Chinese approach: the negative effect of dairy products on the human body and the benefit of soy as a supplement.
2. The vegetarian approach: the negative effect of meat products on the human body and the benefit of soy as a supplement.
3. The Western pro-meat approach: the positive effect of meat products on the human body and the negative effect of soy.
4. The Western pro-dairy products approach: the positive effect of dairy products and the negative effect of soy.

The students were divided into four groups where each group was responsible for creating an ontology for one nutrition approach. The students in each group added statements connected to one of the above approaches and collaboratively created a single-viewpoint ontology. As a result, four ontologies were generated, each of them contained 300 statements representing one of the above nutrition approaches. All the statements included in the ontologies were taken from 260 scientific sources such as academic articles and hospital sites. Finally, the ontologies were compiled into a single multi-viewpoint ontology that comprised 776 statements, including inconsistent statements. After the compilation two information science specialists and a group of 40 crowd workers recruited from the CrowdfFlower website examined each of the statements and labeled them as "true" (564 claims), "viewpoint" (178 statements) and "erroneous" (34 statements) (Zhitomirsky-Geffet, Erez, and Bar-Ilan 2017). Later in the study, the 34 statements labeled as erroneous were excluded from the ontology.

3.3 The multi-theory geometry ontology

Thirteen students training in teaching upper-school mathematics in the academic college discussed the concept of angles and their historical evolution, different uses and various definitions. In addition, they received explanations about ontologies as a model for presenting domain knowledge in information and computer science.

The research literature in the field of geometry, in contrast to the field of nutrition, does not include different viewpoints, but instead different theories. This literature includes statements that exist in one theory and are contrary or contradictory to statements in other theories. Hence, as part of the conducted experiment, the above mentioned 13 students built a multi-theory ontology for geometry. To this end, they received two preliminary ontologies in the field for different theories: Euclidean geometry and hyperbolic geometry (Lobachevsky-Bolyai's geometry). These ontologies were created by an expert in the field based on professional literature. The students were divided into pairs or triplets and were asked to add ontological statements that belong to a different theory, the geometry of a sphere (the Spherical geometry theory) based on professional literature on the subject. As a result of this process three geometry ontologies were obtained and further merged into a multi-theory ontology with 118 statements.

The geometry ontology was built in a different way than the nutrition ontology. While in the latter, each concept constituted a class, and each statement included two concepts and their semantic relationship, in the geometry ontology there were more complex types of statements, such as, "definition", "axiom", "theorem", "basic assumption" and "auxiliary statement". Table 3 exemplifies such complex statements from Lobachevsky's theory and specifies basic concepts (classes) included in them. It can be observed from the table that some of the statements are common for both Lobachevsky's and the Euclidian theories.

The ontology was created in compliance with other ontologies in mathematics, such as the ontology represented in the Hierarchical Editing Language for Macromolecules (HELM) project comprising "terms", "objects" (parallel to statements) and "theories". The Open Mathematical Documents (OMDoc) ontology also contains a similar but a more detailed type structure, i.e., "definitions", "axioms", "proofs", and "theories" (Lange 2013).

To ensure the high accuracy of the outcome, the construction process of both nutrition and math ontologies have been curated and the included ontological statements have been verified by the panel of two domain experts and two ontology engineering specialists.

3.4 Analysis of the ontologies

The analysis of each of the ontologies was done as follows:

1. Identifying inconsistent statements in the ontology by means of building an ontological graph in Python and then detecting the circles in the graph.
2. Mapping the groups of inconsistent statements into one of the eight logic structures described above in order to answer the research questions and to examine the types of inconsistencies existing in them.
3. Applying the multi-viewpoint ontological model from (Zhitomirsky-Geffet, 2019) to resolve the inconsistencies.

4.0 Results

4.1 Nutrition ontology analysis

The nutrition ontology included 742 statements, of which there is consensus regarding 564 statements and the remaining 178 statements are viewpoint dependent. Approximately 35% of the statements are taxonomic relations (A is

Type		Statement	Basic concepts (classes)	Theoretical Framework
1.	Definition	Two straight lines merge when they have two common points	point, straight line	Lobachevsky
2.	Definition	Surface A given a straight line L, if L and A have two common points then L is contained in A.	surface, straight line, point, containing ratio	Lobachevsky
3.	Basic Assumption	Two straight lines perpendicular to a third straight line never intersect	straight line, intersection, perpendicular	Lobachevsky
4.	Axiom	A straight line can be drawn from any point to any point	straight line, point	Lobachevsky
5.	Axiom	Any finite line (segment) can be extended to a straight line (infinite)	segment, finite line, straight line	Lobachevsky Euclidean
6.	Axiom	Every sphere can be defined by means of any center and distance (radius)	sphere, center, distance, radius	Lobachevsky Euclidean
7.	Axiom	All right angles are equal	right angle, equality	Lobachevsky Euclidean
8.	Definition	A right triangle is a triangle in which one angle is a right angle, with sides that are straight lines	right triangle, right angle, straight line, sides of the triangle	Euclidean
9.	Definition	Limit sphere is a sphere with an infinite radius	sphere, limit sphere, infinite radius	Lobachevsky
10.	Axiom	The mid-vertices of all the chords of the limit sphere are parallel to one another	mid-vertices, chord, limit sphere, parallel	Lobachevsky

Table 3. Examples of ontological statements and classes in two geometry theories.

a kind of B) and about 24% include a relationship that shows an increase or decrease (A increases/decreases B) and approximately 16% include meronymy relations (A is part of/contains/includes B). Overall, we found 15 combinations of statements that result in contraries. No combinations of statements were found to cause contradictions.

4.1.1 Structure S1

All the elements of the two statements are equivalent. There were no occurrences of this structure in the ontology, because if equivalent statements exist in the two ontologies they were combined into a single unified statement (by construction). However, a more complex structure was detected that can be converted to S1 as follows:

$$Vp1\text{: } Breast\ cancer\ is\ a\ kind\ of\ cancer$$
$$Vp1\text{: } Breast\ cancer\ is\ a\ kind\ of\ estrogen\ dependent\ cancer$$

There is inclusion among the two objects *(estrogen dependent cancer is a kind of cancer).* Thus, they can be represented as equivalent elements (as shown in Figure 1 in section 3.1 above). Therefore, the subject in these statements has the same relation with the common equivalent subclasses of the objects (*estrogen dependent cancer*), which results in two logically consistent statements.

4.1.2 Structure S2

The relationships and the subjects are equivalent, and the objects are disjoint:

$$Vp1\text{: } Dairy\ products\ cause\ weight\ gain$$
$$Vp2\text{: } Dairy\ products\ increase\ weight\ loss$$

In this case the subjects of the two statements are identical and the relationship of increases is semantically included in the relationship of causes (and thus can be represented as equivalence). The objects of the two statements are semantic opposites (antonyms) and thus create a contrary, as the two statements cannot be true simultaneously, but they can be both false if there is a study that shows that dairy products have no effect on person's weight.

4.1.3 Structure S3

The relationships and the objects are equivalent while the subjects are disjoint. In order to find a contrary in this structure, we can inverse the example provided in Structure S2 (according to ontology rules, inversed statements can be added automatically to every existing statement):

$$Vp1: Weight\ gain\ is\ caused\ by\ dairy\ products$$
$$Vp2: Weight\ loss\ is\ increased\ by\ dairy\ products$$

4.1.4 Structure S4

The relationships are equivalent, and the subjects and objects are disjoint. No contradictions or contraries for this structure were found in the nutrition corpus. There are many statements in the ontology that belong to the structure, but they do not create logical inconsistencies. For example:

$$Vp1: Iron\ decreases\ the\ risk\ of\ breaking\ nails$$
$$Vp2: Isoflavon\ decreases\ the\ risk\ of\ diabetes$$

In this example, the objects and the subjects are disjoint, but they are not antonyms and, therefore, there is no contradiction between the statements. It is noteworthy that theoretically, a contradiction can exist in this structure if the subjects and the objects of the two statements are inversed. Namely, the subject of the first statement is the object of the second statement and vice versa, for instance:

$$Vp1: John\ supervises\ Sharon$$
$$Vp2: Sharon\ supervises\ John$$

If found, we could resolve the contradiction between them only if each one was defined within a different validity scope, such as different time periods or different fields of responsibility.

4.1.5 Structure S5

The relationships are disjoint, and the subjects and objects are equivalent. This structure will always lead to contradictions or contraries as the relationships are semantic antonyms which cannot have common pairs of classes in the same validity scope.

$$Vp1: Dairy\ products\ decrease\ the\ risk\ of\ metabolic\ syndrome$$
$$Vp2: Dairy\ products\ increase\ the\ risk\ of\ metabolic\ syndrome$$

These statements are contraries since they cannot be true in the same validity scope but can be false in the same validity scope if dairy products do not have any effect on the metabolic syndrome.

4.1.6 Structure S6

The relationships and the objects are disjoint, and the subjects are equivalent. No contradictions or contraries that match this structure were found in the nutrition corpus. Many consistent statements can be found that fit this structure, such as:

$$Vp1: Protein\ reduces\ calcium$$
$$Vp2: Protein\ increases\ amino\ acid$$

4.1.7 Structure S7

The relationships and the subjects are disjoint, and the objects are equivalent. Here as well, there are statements that fit this structure, but no statements that lead to contradictions or contraries were found. For instance:

$$Vp1: Plant\ fat\ decreases\ cardiovascular\ disease$$
$$Vp1: Meat\ products\ increase\ cardiovascular\ disease$$

4.1.8 Structure S8

The relations, the subjects and the objects are disjoint: the only statements found in the nutrition corpus that form a contrary in this structure are inversed statements with relations that are antonyms. For example,

$$Vp1: Breast\ cancer\ has\ increased\ risk\ from\ soy\ products$$
$$Vp2: Soy\ products\ prevent\ breast\ cancer$$

All the contraries discussed above can be resolved if the statements are true when the conditions of the study are different. In other words, each of the statements in the inconsistent pair needs to be attributed to a different validity scope, such as a certain research population or experimental setting.

4.2 Analysis of the geometry ontology

The multi-theory geometry ontology included 118 statements from three theories – Euclidean Geometry, Lobachevsky's Geometry and Spherical Geometry. The distribution of different types of statements in each theory are presented in Table 4 below.

Fourteen combinations of statements that lead to a contrary were found in the geometry ontology.

Type of Statement	Euclidean Geometry		Lobachevsky's Geometry		Spherical Geometry	
	Quantity	Percent	Quantity	Percent	Quantity	Percent
Axioms	10	14.9%	5	14.3%	6	37.5%
Definitions	3	4.5%	10	28.6%	3	18.7%
Theorems	54	80.6%	18	51.4%	7	43.8%
Auxiliary Statement	0	0.0%	1	2.9%	0	0.0%
Basic Assumptions	0	0.0%	1	2.9%	0	0.0%
Total	67	100.00%	35	100.00%	16	100.00%

Table 4. Types of statements in the geometry ontology.

4.2.1 Structure S1

The relationships, the subjects and the objects have common members. As in the nutrition ontology no inconsistencies (and not statements at all) matching this structure were found.

4.2.2 Structure S2

The relationships and the subjects are equivalent, and the objects are disjoint. In Euclidean geometry the smallest number of sides in a polygon is three whereas in Spherical Geometry it is two, therefore we obtain these two statements:

Vp1: Polygon – contains a minimum number of sides – three.
Vp2: Polygon – contains a minimum number of sides – two.

This is a contrary because the objects of the two statements "three" and "two" are disjoint in the given context. That is, the minimum number 3 does not coexist with the minimum number which is 2. We note that the two statements are not a contradiction (but only a contrary), since (hypothetically) they can both be false in the case that there is a different minimum number of polygon's sides according to another theory.

4.2.3 Structure S3

The relationships and the objects are equivalent, and the subjects are disjoint. We can change the order of the statements of Structure S2 in order to obtain the contrary that exists in the corpus:

Vp1: Three – is the minimum number of sides in - a polygon.
Vp2: Two – is the minimum number of sides in - a polygon.

4.2.4 Structure S4

The relationships are equivalent, and the subjects and objects are disjoint: the statements in the corpus that suit this structure are not contradictions or contraries. For example:

Vp1: The longest side in a triangle - is opposite - the largest angle in the triangle.
Vp2: The largest angle in a triangle - is opposite - the longest side in the triangle.

The statements are logically consistent since "is opposite" is a symmetric relationship.

4.2.5 Structure S5

The relationships are disjoint, and the subjects and objects are equivalent)#:

Vp1: The sum of the angles in a triangle – is equal to - 180 degrees.
Vp2: The sum of the angles in a triangle – is greater than - 180 degrees.

Similar to the analysis done in the nutrition ontology, here as well the reason for the contrary is the logically and semantically incompatible relationships in the two statements which always lead to inconsistencies. The relationship "greater than" and the relationship "equal to" cannot coexist for the same pair of classes that appear in the same physical conditions, i.e., validity scopes. Indeed, the first statement is valid in a plane and the second in a sphere.

4.2.6 Structure S6

The relationships and the objects are disjoint, and the subjects are equivalent): in order to obtain a contrary in this structure we split the following statement into two:

Vp1: The *exterior angle of a triangle is less than or equal to the nonadjacent interior angle.*
(1) The exterior angle of the triangle – is less than – the nonadjacent interior angle.
(2) The exterior angle of the triangle – is equal – to the nonadjacent interior angle.

Now we have a contrary with statement Vp_2:

Vp1: The exterior angle of a triangle – is less than – the nonadjacent interior angle.
Vp2: The exterior angle of a triangle – is equal to – the sum of two nonadjacent interior angles.

In this example we obtain an indirect contrary, because an implicit statement exists (a statement that is not usually noted, because it is obvious) that the sum of two angles is not less than one of them. Thus, the objects and relationships are disjoint from one another. Consequently, the statements are a contrary, because nothing exists that is less than another object and also equal to it.

4.2.7 Structure S7

The relationships and the subjects are disjoint, and the objects are equivalent: in order to obtain a contrary in this case we can inverse the relations in the above example that exists in Structure S6:

Vp1: The nonadjacent interior angle – is greater than – an exterior angle in the triangle.
Vp2: The sum of two nonadjacent interior angles – is equal to – an exterior angle of the triangle.

4.2.8 Structure S8

The relationships, the subjects and the objects are disjoint: no contradictions or contraries were found in this corpus that match this structure. Only logically consistent statements were found. For example:

Vp1: An exterior angle of the triangle – is equal to – the sum of two nonadjacent interior angles.
Vp2: The sum of the angles in the triangle – are greater than - 180 degrees.

Table 5 summarizes the findings of the ontological inconsistency analysis. After applying the unified multi-viewpoint/multi-theory ontology model, we observe that each of the contrary statements are defined in different validity scopes, for instance, on a spherical space or alternatively on a plane, in the Euclidean or non-Euclidean space. Thus, they can be associated with their validity scopes and then unified into one consistent ontological model.

5.0 Discussion and conclusions

The main conceptual contribution of the study are the new generic logical structures for inconsistency detection in multi-viewpoint and multi-theory ontologies that are generally based on the description logic principles. The main methodological contribution is the developed framework for systematic detection and classification of ontological inconsistencies by mapping pairs of various ontological statements to these structures. The approaches presented in previous research focus on individual ontological statements and their epistemological characteristics, e.g. locality/universality (Hemam, Djezzar and Djoud 2016; Djakhdajkha,

Logical Structure	Inconsistency detected in	
	Nutrition Ontology	Geometry Ontology
S1: $A \equiv C, R \equiv Q, B \equiv D$		
S2: $A \equiv C, R \equiv Q, B \cap D = \emptyset$	V	V
S3: $A \cap C = \emptyset, R \equiv Q, B \equiv D$	V	V
S4: $A \cap C = \emptyset, R \equiv Q, B \cap D = \emptyset$		
S5: $A \equiv C, R \cap Q = \emptyset, B \equiv D$	V	V
S6: $A \equiv C, R \cap Q = \emptyset, B \cap D = \emptyset$		V
S7: $A \cap C = \emptyset, R \cap Q = \emptyset, B \equiv D$		V
S8: $A \cap C = \emptyset, R \cap Q = \emptyset, B \cap D = \emptyset$	V	

Table 5. Summary of the inconsistency analysis of the two ontologies.

Hemam and Boufaida 2014; Djakhdjakha, Hemam and Boufaida 2012; Gnoli and Szostak 2014; Szostak 2014; Tennis 2016; Zhitomirsky-Geffet et al. 2017), and context (Baclawski, Kokar and Matheus 2003; Kokar, Matheus and Baclawski 2009; Welty 2010; Giménez-García et al. 2017). However, the determination of such characteristics might be quite challenging, subjective and viewpoint dependent. On the contrary, the proposed method scans the ontology and identifies *pairs* of ontological statements that match one of the logical structures associated with potential inconsistencies. This approach makes inconsistency detection systematic and straightforward since it pinpoints. We have also shown that the detected inconsistencies can be resolved by applying the unified multi-perspective model of Zhitomirsky-Geffet (2019).

The structures that were found include: Structures S1-S4 used in cases of equivalent relationships: 1) The subjects and also the objects are equivalent; 2) The subjects are equivalent, and the objects are disjoint; 3) The subjects are disjoint, and the objects are equivalent; 4) The subjects are disjoint and also the objects are disjoint; and Structures S5-S8 used in cases of disjoint relationships: 5) The subjects and the objects are equivalent; 6) The subjects are equivalent and the objects are disjoint; 7) The subjects are disjoint and the objects are equivalent; 8) The subjects are disjoint and also the objects are disjoint.

The two ontologies were analyzed, and contraries were found in six of the eight structures: structures S2, S3, S5, and S8 in the nutrition ontology, and structures S2, S3, S5, S6 and S7 in the geometry ontology. All in all, contraries were found in all structures excluding structure S1 (in which the statements are always logically equivalent) and structure S4 (in which a contrary can exist hypothetically but is quite rare and was not revealed in the examined ontologies). The results of this study also show that only the structures S2, S3, and S5 led to contraries in both ontologies. However, finding certain structures in one corpus and not in the other, does not necessarily indicate that certain types of inconsistencies can exist only in one domain. Interestingly, our findings demonstrate that general logical disjointness does not usually causes inconsistencies, but only when combined with semantic antonymy.

Finally, in order to address the third research question of this study related to inconsistencies' resolution, a simple solution could be to employ the Argumentation (I1) and Belief (I2) classes definition from CIDOC-CRMinf. These classes associate an instance of the Actor (E39) or a Group of actors (E74) who justifies and believes that a given ontological statement (or a set of statements) is true at a certain time period. However, after analyzing the two ontologies, it turned out that this approach only provides a partial solution as inconsistencies can happen not only because of temporal constrains or due to beliefs of specified authors, but because both statements are true under a different set of conditions, i.e., validity scopes, such as types of populations, experimental settings (nutrition domain), or physical conditions (geometry domain). Thus, we proposed a more general solution which assigns relevant validity scope(s) to each statement. Then, according to Zhitomirsky-Geffet's model (2019), these statements can be included in the unified ontology of the domain in a consistent manner.

The current research has practical implications for decision-support systems (DSS) (Ghatee et al. 2014), search engines (SE) and question answering systems (QAS) (Geryville et al. 2007; Rawal et al. 2020). DSS and QAS can cross-analyze the different validity scopes in the multi-viewpoint ontology with the personal preferences of the user, in order to infer which answer is the most relevant for the specific user. The statements selected in the system's reply will belong to the validity scope most closely related to user's preferences. Similarly, the model can assist in providing diversified search results insofar as many users might be interested in learning about other's preferences and opinions (An, Quercia and Crowcroft 2013). Using the logical framework presented in the current research can be of assistance in such SE. Due to the domain division into viewpoints or theories, that is reflected in the multi-viewpoint ontological model, SE and DSS can clearly present the relation of every search result to the relevant viewpoint or theory. Moreover, using validity scopes can shed light on why the inconsistency exists in the knowledge domain in the first place.

This research has certain limitations. The analysis was conducted only on two ontologies from two different knowledge domains. To generalize the findings and conclusions, in future research we intend to apply the proposed framework for inconsistency detection and classification on additional large-scale multi-viewpoint ontologies from a variety of domains.

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