Formal Ontology and the Foundation of Knowledge Organization

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ABSTRACT: Research in ontology has, in recent years, become widespread in the field of information systems, in various areas of sciences, in business, in economy, and in industry. The importance of ontologies is increasingly recognized in fields diverse as in e-commerce, semantic web, enterprise, information integration, information science, qualitative modeling of physical systems, natural language processing, knowledge engineering, and databases. Ontologies provide formal specifications and harmonized definitions of concepts used to represent knowledge of specific domains. An ontology supplies a unifying framework for communication, it establishes a basis for knowledge organization and knowledge representation and contributes to theory formation and modeling of a specific domain. In the current paper, we present and discuss principles of organization and representation of knowledge that grew out of the use of formal ontology. The core of the discussed ontological framework is a top-level ontology, called GFO (General Formal Ontology), which is being developed at the University of Leipzig. These principles make use of the onto-axiomatic method, of graduated conceptualizations, of levels of reality, and of top-level-supported methods for ontology-development. We explore the inter-relations between formal ontology and knowledge organization, and argue for a close interaction between both fields.

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1.0 Introduction

In this paper, we present and discuss principles of organization and representation of knowledge which are grounded on formal ontology and the axiomatic method, being unified to establish the onto-axiomatic method. We use the term formal ontology (FO) to name an area of research which is becoming a science similar to formal logic. Formal ontology is concerned with the systematic development of axiomatic theories describing forms, modes, and views of being of the world at different levels of abstraction and granularity. Formal ontology integrates aspects of philosophy, formal logic, artificial intelligence (computer science), and cognitive science.

Knowledge organization (KO), being a subfield of library and information science (LIS), is focused on the classification of knowledge fields and of concept formation (Hjørland 2008, 2009). In Hjørland (2008), the following six approaches to KO are described in more detail: the traditional approach, exemplified by Bliss (1935); the facet-analytical approach, founded by Ranganathan (1933); the information retrieval tradition, discussed by Warner (2002); user-oriented views; bibliometric approaches; and domain analytic methods. The approach presented in the current paper cannot be subsumed by one of these approaches, though there are close relations to some of them that will be explicated throughout the paper.

Basic units of KO, according to Anderson (2003), are the following six kinds of entities: message, knowledge, text, artifact, information, document. These entities are to be organized and connected by semantic relations and bibliographic relationships. A classification schema in KO consists of a set of concepts and relations connecting them; neither the concepts nor the relations are made explicit by introduction of formal axioms. The focus and purpose of formal ontology differs from this approach because an ontology is presented by a system of axioms which can be used to draw conclusions, to generate hypotheses, to interpret data by annotations, and to solve problems in the corresponding domain by computer-based methods. On the other hand, ontologies are included in the layer of knowledge organization systems, addressed in Gnoli (2011). Hence, both disciplines overlap.

A core topic of both KO and formal ontology is the creation of conceptualizations. According to Gruber (1993), who introduced the term ontology in computer science, an ontology is a formal specification of a conceptualization. We use the term ontology to name formal knowledge systems in the sense of Gruber, and the term formal ontology as a research direction. Some relations between formal ontology and KO are discussed in Dahlberg (2008), where a theoretical basis for the Information Coding Classification is established. This theory includes an integrative level theory, an approach of ontical areas, and the application of a feature of system theory.

A basic task of formal ontology consists of an analysis of systems of terms, denoting concepts, and in translating them into formal theories, which are the basis for various applications. In KO and LIS several sorts of information artefacts are developed, like coding systems, keyword sets, controlled vocabularies, and classifications (Keizer 2000). These systems exhibit an important basis for ontological investigations; they can be integrated in the field of formal ontology (Herre 2010b). There is another problem in the field of KO which is closely related to formal ontology: the establishment of a system of most general categories. This is a task of top-level ontologies, and there are various alternatives for such systems, as discussed in Herre (2010a).

Another core topic of KO is the establishment of concept theories (Hjørland 2009). In Dahlberg (2008), four kinds of relationships between concepts are introduced: the generic, the partitive, the complementary, and the functional. Using these relations, concept systems can be generated. Most of the current top-level ontologies do not contain an ontology of concepts, with the exception of GFO (General Formal Ontology), which includes a structural theory of concepts, (Herre et al. 2007; Herre 2010a). In contrast to GFO, other top-level ontologies, notably BFO (Basic Formal Ontology), exclude concepts from ontology, (Smith 2004; Smith, Ceusters, and Temmermann 2005). GFO reconciles ontology with epistemology by the idea of integrative realism, and by including multiple basic types of categories. From this follows that the approach taken by GFO establishes a firm ground for a fruitful interaction between formal ontology and KO.

The paper is organized as follows. In section 2, we present the basics of the onto-axiomatic method. Section 3 contains an overview on the GFO-framework, and section 4 is devoted to the structure and representation of concepts. In section 5, we give an overview on some applications of formal ontology. Finally, in section 6, some application of the methods are summarized, and various problems for future research are collected.

2.0 The onto-axiomatic method

Information is available in various levels of detail, from primary data, to metadata and to knowledge. Metadata are used to describe data, hence, they add more precise meaning to data, the semantics of which remains often underspecified. Since the metadata must be specified by some formal representation, the meaning of which should be explained, we arrive at an infinite regress which must be brought to an end by some basic principle, as discussed in Herre and Loebe (2005). In our approach, this infinite regress is blocked by using a top-level ontology and suitable domain-specific extensions of it that provide the most basic layer for a semantic foundation. Furthermore, the meaning of the top-level ontology's categories and relations and its domain-specific extensions is established by the axiomatic method, introduced in mathematics by Hilbert (1918). We call this method, which integrates the axiomatic method with a top-level ontology and its extensions, the onto-axiomatic method.

The main building blocks of knowledge are concepts, relations, and axioms, specified in a suitable formal language. The concepts and relations, associated to a domain D, are classified into primitive and defined concepts and relations. Given the primitive concepts and relations, we can construct formal sentences which describe formal-logical interrelations between them. Some of these sentences are accepted as true in the domain under consideration; they are chosen as axioms without establishing their validity by means of a proof. These axioms define the primitive concepts implicitly, because the concepts' meaning is captured and constrained by them. The onto-axiomatic method establishes new principles for structuring and ordering of knowledge; in Herre and Loebe (2005), a three level architecture is introduced.

The most difficult methodological problem concerning the introduction of axioms is their justification. In general, four basic problems are related to an axiomatization of the knowledge of a domain. Which are the appropriate concepts and relations for a domain (problem of conceptualization)? How we may find axioms (axiomatization problem)? How can the (relative) truth of the axioms be supported (truth problem)? How can we establish or support the consistency of the resulting theory (consistency problem)?

The choice and introduction of adequate concepts and relations is a crucial one, because the axioms are built upon them. Without an adequate conceptual basis, we cannot establish relevant axioms for describing the domain. An inappropriate choice of the basic concepts for a domain leads to the problems of irrelevance and conceptual incompleteness. Furthermore, the relevance of change of concepts must be taken into consideration

Ontologies exhibit different levels of abstraction; top-level ontologies, for example, apply to any domain of interest, whereas upper-domain and domain ontologies are related to more restricted domains. There are no established rules to separate these levels of abstraction, though there is tendency to understand the axioms of a top-level ontology as analytic truths. Quine (1951) emphasized that a clear separation between analytic and synthetic truths cannot be made; on the other hand, top-level ontologies are the most basic and they play—in a sense—a pseudo-analytical role. The interrelations between ontologies of different levels of abstraction needs further investigation, and a contribution to a formal-logical analysis is presented in Palchunov (2005). We distinguish four basic types of domains: the domain of the material world, the domain of the mental-psychological world, the domain of the social world, and, finally, the domain of abstract, ideal entities. Basic ideas on these ontological regions were established by Hartmann (1964), and further elaborated by Poli (2001). It is an important task of the onto-axiomatic method to develop means to support the solution of the basic problems mentioned above. This is work in progress.

3.0 The GFO-framework

In this section, we give an overview of the GFO-framework; a more detailed exposition is presented in Herre (2010) and Herre et al. (2007). General Formal Ontology (GFO) is a top-level ontology which is being developed at the university of Leipzig.

3.1 Categories, instances, and modes of existence

The term "entity" covers everything that exists, where existence is understood in the broadest sense. We draw on the theory of Ingarden (1964) who distinguishes several modes of being: absolute, ideal, real, and intentional entities. The basic distinction of entities is between categories and instances. A category is an entity, being independent of time and space, which can be predicated of other entities. The predication relation is closely related to the instantiation relation, and the feature of being instantiable holds only for categories.

On the opposite, individuals are singular entities which cannot be instantiated. The instances of a category are not necessarily individuals, they can be categories again. Categories are entities expressed by predicative terms of a formal or natural language that can be predicated of other entities. Predicative terms are linguistic expressions which specify conditions to be satisfied by an entity. There is a close relation between categories and language, hence, any analysis of the notion of a category must include the investigation of language.

3.2 Universals, concepts, and symbols

We draw on the ideas of Gracia (1999), who distinguished various basic types of categories. We distinguish at least three kinds of categories: universals, concepts, and symbol structures. Universals are categories which are independent of the mind; they are classified into intrinsic and ideal universals. Intrinsic universals are constituents of the mind-independent material world; they are associated to invariants of the spatio-temporal real world, and they are something abstract that is in the things. Ideal universals are existentially independent of the material real world and of the mind, as for example numbers, geometric entities, and platonic ideas.

Concepts are categories that are represented as meanings in someone's mind. Concepts are a result of common intentionality which is based on communication and society. We hold that universals can only accessed through concepts, hence for the establishing of knowledge the category of concepts is the most important one. Symbols are signs or texts that can be instantiated by tokens. There is a close relation between these three kinds of categories: a universal is captured by a concept which is individually grasped by a mental representation, and the concept and its representation are denoted by a symbol structure being an expression of a language. Texts and symbolic structures may be communicated by their instances that a physical tokens.

3.3 Ontological basic distinctions

Entities are classified into categories and individuals. The basic entities of space and time are chronoids and topoids; these are considered as individuals. The ontology of space and time is inspired by ideas of Brentano (1976). The GFO theory of time is presented in Baumann et al. (2012). Individuals are divided into concrete and abstract. Concrete individuals exist in time or space, whereas abstract individuals are independent of time and space. According to their relations to time, concrete individuals are classified into continuants, presentials and processes. Processes happen in time and are said to have a temporal extension. Continuants persist through time and have a lifetime, which is a chronoid. A continuant exhibits at any time point of its lifetime a uniquely determined entity, called presential, which is wholly present at the (unique) time boundary of its existence.

Examples of continuants are this ball and this tree, being persisting entities with a lifetime. Examples of presentials are this ball and this tree, any of them being wholly present at a certain time boundary t. Hence, the specification of a presential additionally requires the declaration of a time boundary. In contrast to a presential, a process cannot be wholly present at a time boundary. Examples of processes are particular cases of the tossing of a ball, a 100m run as well as a surgical intervention, the conduction of a clinical trial, etc. For any process p having the chronoid c as its temporal extension, each temporal part of p is determined by taking a temporal part of c and restricting p to this sub-chronoid. Similarly, p can be restricted to a time boundary t if the latter is a time boundary or an inner boundary of c. The resulting entity is called a process boundary, which does not fall into the category of processes.

3.4 Levels of reality

We assume that the world is organized into strata, and that these strata are classified and separated into layers. The term "level" denotes both strata and layers. This approach is inspired by Hartmann (1964) and Poli (2001). GFO distinguishes at least four ontological strata of the world: the material, the mental-psychological, the social stratum, and the region of ideal entities. Every entity of the world participates in certain strata and its levels. We defend the position that the levels are characterized by integrated systems of categories. Hence, a level can be understood as a meta-category, the instances of which are certain types of categories. Among these levels specific forms of categorical and existential dependencies hold. For example, a mental entity requires an animate material object as its existential bearer. The strata to which categories should be placed must then be determined. Concepts are rooted in the psychological and social stratum, and the investigation of this ontological region must use results of cognitive science, see Murphy (2004) and Gärdenfors (2000). In contrast to top-level ontologies as BFO (Spear 2006) and DOLCE (Borgo and Masolo 2010), the top-level ontology GFO (Herre 2010) includes an ontology of categories, the most important of which are the concepts.

3.5 Integrative realism

GFO introduces a new form of realism. Realism assumes the existence of a mind-independent real world. Yet the basic assumption of the GFO-approach is grounded on the idea of integrative realism. This kind of realism postulates a particular relation between the mind and the independent material reality. This relation connects dispositions of a certain type, inhering in the entities of material reality, with the manifold of subjective phenomena occurring in the mind. This relation can be understood as unfolding the real world disposition X in the mind's medium Y, resulting in the phenomenon Z. In this ternary relation, the mind plays an active role. In GFO, continuants are viewed as cognitive creations of the mind that possess features of a universal, occurring as the phenomenon of persistence, but also of spatio-temporal individuals, grounded on the presentials, which the continuants exhibit. This approach is supported by results of cognitive psychology, notably in Gestalt theory (see Wertheimer 1922). The integrative realism reconciles ontology and epistemology.

We hold that mind-independent entities (being in the realm of the material region or of the region of platonic ideas) can be only accessed by concepts and symbolic structures. Furthermore, the integrative realism must additionally consider the relations between the other ontological regions. The investigations of the relations, connecting the ontological regions, is a topic of research which faces various unsolved problems. One of the big problems concerns the relation between mind and body (Inwagen and Zimmermann 1998). The theory of integrative realism differs from the kind of realism defended by BFO (Spear 2006). Recently, there started a debate—initiated by Merril (2010)—about the interpretation and role of philosophical realism, and, in particular, about the type of realism, defended by Smith in numerous papers (cf., Smith 2004, 2006). We believe that integrative realism overcomes weaknesses of the type of philosophical realism defended in Smith (2004).

3.6 Development of ontologies and approaches to KO

We summarize the basic steps for the development of an ontology, according to the GFO methodology. It turns out that several of these steps are closely related to some of the approaches to KO presented and discussed in Hjørland (2008, 2009). An ontology usually is associated with a domain, hence, we must gain an understanding of the domain which is under consideration.

3.6.1 Step: domain specification, task specification, and proto-ontology

A specification DomSpec(D) of a domain D is determined by the entities to be considered by classification principles and a set of views. There is a great variety of classification principles, as emphasized by Hjørland (2013b). A task specification TaskSpec(D) describes the tasks which are intended to be solved by the ontology's usage. The considered entities Ent(D) of the domain D are determined by the assumed views, whereas the classification principles provide the means for structuring the set Ent(D). Usually, there is source information which is associated to the domain, in particular a set *Terms*(D) of terms denoting concepts in the domain. The system ProtoOnt(D) = (DomSpec(D) ∪ TaskSpec(D), Terms(D)) is called a proto-ontology. The development of a proto-ontology integrates various approaches to KO, as classified in Hjørland (2008), notably the user-oriented view, and the domain analytical approach. A proto-ontology of a domain contains the relevant information needed to make the further steps in developing an axiomatized ontology.

3.6.2. Step: conceptualization

A conceptualization is based on a proto-ontology; the result of this step is (optionally) a graduated conceptualization (see section 4). Hence, the principal and elementary concepts of the domain must be identified or introduced. The resulting concepts belong either to the concepts denoted by the terms of Terms(D), or they are constructed by means of the classification principles. A further substep pertains to the desired aspectual concepts which are derived from the elementary concepts. Finally, we must identify relations which are relevant to capture content about the individuals and concepts. It would be helpful if a meta-classification of relations were available. GFO provides already a basic classification of relations which must be extended and adapted to the particular domain D. There is relation between the conceptualization step and the facet-analytical approach.

3.6.3 Step: axiomatization

During this step, axioms Ax(Conc ∪ Rel) for the concepts and relations are developed. This needs a formalism, which is usually a formal language (FOL. OWL, RDF). A final axiomatization for Conc(D) ∪ Rel(D) can be achieved by starting with a top-level ontology, say GFO, and then constructing by iterated steps an ontological mapping from Conc(D) ∪ Rel(D) into a suitable extension of GFO. The axiomatization step, being assisted by a top-level ontology, includes three sub-steps: The addition of new primitive concepts, the creation of axioms for these concepts, and the introduction of new concepts by definitions. The introduction of concepts by definitions pursues a similar philosophy as facet-analysis, though, the definability method allows, depending on the language used, more combinations of given concepts and relations.

A relevant feature of the axiomatization step in GFO is the linking of domain specific concepts and relations with the axioms of the top-level ontology. There is, for example, the following axiom of the top-level:

$\forall x\ (MatStr(x) \rightarrow \exists\ y\ (SRegion(y) \wedge occ(x,y)$ (Every material structure occupies a space region).

The following axiom is a linking axiom:

$\forall x\ (Tree(x) \rightarrow MatStr(y))$.

From these axioms, we may derive that every tree occupies a space region.

The organization of knowledge by the onto-axiomatic method seems to be a new approach to KO, not mentioned in the classification, discussed in Hjørland (2008). Another unique selling feature of this approach is the use of a top-level ontology which supports the development of the axiomatization. The development of tools and methods, supporting the axiomatization step, is an important research topic (Herre and Heller 2006).

4.0 Graduated conceptualizations, the structure of concepts, and sets

In this section, we consider principles for the organization of conceptual systems preceding the axiomatization step. Graduation and the structure of concepts exhibit implicit interrelations to facet analysis.

4.1 Graduated conceptualizations and layered axiomatization

The set Conc(D)∪ Rel(D) of concepts and relations, associated to a domain D, is divided into a set of principal concepts of D, denoted by PrincConc(D), into a set of elementary concepts, designated by ElemConc(D), into a set of aspectual concepts of D, symbolized by AspConc(D), and into logically defined concepts, denoted by LogConc(D). These sets of concepts form an increasing chain, i.e., we suppose that PrincConc(D) ⊆ ElemConc(D) ⊆ AspConc(D) ⊆ LogConc(D). The principal categories are the most fundamental of a domain. For the biological domain, the concept of organism is considered as principal. The system (PrincConc(D), ElemConc(D), AspConc(D), LogConc(D)) is called a graduated conceptualization for the domain D; the components PrincConc(D) and ElemConc(D) are considered as mandatory, the other as optional.

The elementary categories of a domain are introduced and determined by a classification based on the domain's classification principles; they should contain a taxonomy as a scaffold. In addition to the elementary categories, there is an open-ended set of aspectual categories, derived from the fact that any entity stands in many relations to other entities. The notion of aspectual analysis has a relation to the notion of facet analysis in Ranganathan (1933). The notions of aspectual composition and deployment are concerned with the construction of new concepts from constituents.

New concepts can be introduced along dimensions or basic aspects. Basic aspects are concepts or basic relations of a top-level ontology, which is in the sequel GFO. An intuitive, informal relation aspect ($X, Y_1, ..., Y_n, Z$) means: X is a domain concept, Y_i is a basic concept, or a basic relation of GFO and Z a category derived from X using the concepts or relations Y_i in the role of an aspect. Therefore, Z is an aspectual concept of X via $Y_1,..., Y_n$. Let us consider an example. The notion X of hedgehog is a concept, a species. The notion of space and time are basic concepts of GFO; then the concept Z, the instances of which are those hedgehogs living in Germany (spatial location Y_1), during the time-interval Y_2 (temporal location) exhibits an aspectual derivation of X via Y_1, Y_2.

4.2 Structure of concepts

The structure and architecture of concepts is concerned with their composition and parts, as well as their formal representation, types, and combining relations. The instantiation relation, denoted by the symbol ::, is one of the combining relations for concepts; it uncovers the type of the concepts. The set of types is the smallest set of expressions, containing the symbol 0 and which is closed with respect to the following condition: If $\tau_1,..., \tau_n$ are types, then the set $\{\tau_1,..., \tau_n\}$ is a type. The type of a concept or an individual is inductively defined as follows. Individuals have the type 0. A concept C has type τ, denoted by type(C), if $\{type(a) \mid a :: C\} = \tau$. A concept is said to be well-founded if it possesses a type. There might be concepts which are not well-founded. An ontology of non-well-founded concepts must include ideas of non-well-founded set theory (see Aczel 1988; Devlin 1993).

A primitive concept has type $\{0\}$, hence, all its instances are individuals. Any non-primitive concept is called higher-order concept. The biological concept "species" has structural type $\{\{0\}\}$ because every instance is itself a concept having the type $\{0\}$. Domain level concepts, also called meta-concepts of domains, have as their instances all concepts associated to the corresponding domain; hence, they are always higher order concepts.

Furthermore, concepts may have conceptual parts, derived from combining relations. In the most simple case, a concept may be considered as set of properties (Ganter 1996). A conceptual part of a concept is either itself a concept or a designation of an individual. The relation of categorial part, denoted by catp(x.y), with the meaning that x is a categorial part of the concept y, can be interpreted into two directions. The first interpretation is that every concept of the transitive closure of C is a categorial part of C. The second interpretation expresses the idea that the categorial parts are arguments of more complicated combining relations, based, say, on a relations of type "has-property." A very complex type of concepts exhibit whole theories, the parts of which are concepts of different structural type that are related and connected by relations and logical functors.

A knowledge field, say biology, can be understood as a concept the instances of which include all the field's concepts. With this interpretation a knowledge field is always a concept of higher order. In Fricke's (2010) paper, it is stated that the top-level ontologies BFO and DOLCE are not adequate for coping with concepts of higher order. We emphasize that all problems mentioned in Fricke (2010) can be easily solved within the GFO-framework.

5.0 Applications

The field of formal ontology and its applications is in its initial stage. We consider various types of applications, which grew out from our work, and collect several open problems being at the borderline of formal ontology and knowledge organization. There are three types of applications of formal ontology: Computer-based applications, harmonization of concepts, and theory formation, including analysis, and modeling.

1) Computer-based applications use ontologies as a component of software. There is broad spectrum of applications in the field of the semantic web. An example of such applications are presented in Hoehndorf, Kelso and Herre (2009) and in Hoehndorf et al. (2009).
2) Harmonization of concepts is needed to develop a common basis for communication and for establishing a discipline. The result of a harmonization process is an ontology which explicates and organizes the conceptual knowledge of a field, for example in Hoehndorf et al. (2008) GFO-Bio, for the harmonization of the upper concepts of biology.
3) Theory formation, analysis, and modeling are concerned with the development of top-level ontologies, which are used for the ontological analysis of a field of interest. Formal ontology as a science provides a support for theory formation and for the creation of models for a domain. An example of this kind of application is the theory of sequences as expounded in Hoehndorf et al. (2009). Other applications of this kind are presented in (Baumann et al. 2012) on the ontology of time.

6.0 Future Research

We collect some tasks for the future research. Gnoli (2008) asked whether KO principles can be extended to a broader scope, including hypertext, multimedia, museum objects, and monuments. Multimedia includes a combination of text, audio, graphics, images, animation, video, or interactivity content forms. This can be achieved by the development of a sufficient expressive ontology of information entities. The development of such an ontology is work in progress. A further problem is related to the role of top-level ontologies in KO. They may bridge, by using the described method of ontology development, the domain-analytical approach with the design of classification systems for bibliographic databases; this problem is addressed in Hjørland (2013b).

An interesting project is the ontological foundation of facet theory. Various authors remark that the original ideas of Ranganathan (1933, 1957, 1965, 1998) are rather vague and insufficiently established (Hjørland 2013a; Spiteri 1998; La Barre 2010). We believe that the GFO-framework is sufficient expressive to allow a ontological reconstruction of facet theory. Such a reconstruction could provide a deeper understanding of notions as facet, subject, idea, isolate, etc. This is work in progress.

Finally, the structure and formal representation of concepts, notably of higher order concepts, is not yet sufficiently understood. One may say that a concept can be unfolded by adding aspectual categories, derived from it. Aspectual categories of a category add further information and show how the instances of a concepts can be further structured.

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