Formal Ontology - A New Discipline Between Philosophy, Formal Logic, and Artificial Intelligence

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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, library and information science, qualitative modeling of physical systems, natural language processing, knowledge engineering, and databases. 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 outline basic principles of formal ontology, being an evolving science which integrates aspects of philosophy, formal logic, and artificial intelligence. A central feature of formal ontology is the onto-axiomatic method which includes as a core component a top level ontology. We summarize the principles of the top level ontology GFO (General Formal Ontology) which is being developed at the university of Leipzig. The various sources of formal ontology are explicated and exemplified, and it is demonstrated that formal ontology is more than an eclectic aggregrate of the mentioned research areas.

1. Introduction

We use the term *formal ontology* (FO) to name an area of research which is becoming a science similar as 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. This science integrates, among others, aspects of philosophy, formal logic, and artificial intelligence. An inspiring model for formal ontology is provided by set theory which can be understood as an ontological basis for classical mathematics. Formal ontology seeks to extend the axiomatic set theory to an axiomatic theory which is expressive enough to describe areas of the world, being different from mathematics, among them, the material world of the natural sciences, psychology, and the world of socio-systemic structures. For this purpose formal ontology must clarify which modes of existence should admitted to cover all relevant ontological regions.

The top level ontology General Formal Ontology (GFO) aims at achieving such a general framework, the elaboration of which is a long-lasting project. GFO (General Formal Ontology) is a component of ISFO (Integrated System of Foundational Ontologies), and ISFO is intended to be a part of an Integrated Framework for Development and Application of Ontologies (IFDAO). GFO is not intended to be the ultimate result of a foundational ontology; one may doubt whether a final and uniquely determined top level ontology can ever be achieved. For this reason, GFO is merely a component of the evolutionary system ISFO, which leaves room for modifications, revisions, adaptations that are triggered by the historical state of our knowledge, and the applications in nature and society.

In section 2 various contributions from philosophy are exemplified, and section 3 the influence of artificial intelligence and computer science on formal ontology is discussed. In section 4 we expound relevant contributions of formal logic, which consists in the axiomatic method and related topics. The framework of GFO is presented in section 5, and section 6 outlooks various future topics and problems.

The current paper gives a condensed overview on main aspects of formal ontology, the details of which are presented and distributed among various papers of the author, in particular in (Herre 2007), (Herre 2010), and (Herre 2013). Our approach to formal ontology exhibits a bridge to the methods and the ideas presented in the seminal works by G. Klaus, in particular in (Klaus 1965). Behind Georg Klaus` ideas arises the vision of a new and free society, the basis of which is the automatization of labour, realized by cybernetics, and by the current methods of artificial intelligence. The establishment of such a society is an urgent task for the future.

2. Philosophical Contributions to Formal Ontology

Ontology as a branch of philosophy is the science of what is, of the kinds and structures of objects, properties, processes and relations in every area of the world. We defend the opinion that philosophical ontology should be engaged in a factual inquiry of the nature of reality. In particular, philosophical ontology should contain, as a part, a descriptive theory of categories, used to classify the entities in the world. Such a classification schema is a weak form of axiomatization. Build upon a classification theory, further axioms must be developed to achieve a deeper understanding of the structure and the laws of the world. Philosophers developed various categorical systems for the description of the world which is a suitable starting point for elaborating an exhaustive foundational ontology. The philosophical sources of formal ontology, as expounded in this paper, are provided by various authors, among them, by Aristoteles (1998,1999), by Hartmann (1965), Brentano (1976), Husserl (1913, 1901), Ingarden (1964), Marx (2008), Hegel (1971), Gracia (1999), and Lewis (1986a, 1986b, 1999).

Important contributions were provided by the phenomenological philosophy, grounded by Franz Brentano, and further elaborated by E. Husserl, and his disciples. Many classical problems in philosophy are problems in ontology; they deal with whether or not a certain thing exists. Though, formal ontology additionally includes problems about the most general features and relations of the entities which exist, and the mode of its existence.

In summary, there are three fundamental aspects, being studied in philosophical ontology, the results of which provide an important source of ideas and methods, to be included in the discipline of formal ontology.

(1)The study of what there is, and what modes of existence there are;

(2) The study of the most general features of what there is, and how the things are related to each other.

(3) The study of meta-ontology, explicating tasks and results, the discipline of ontology aims to accomplish, and with what methodology these tasks are realized.

An ontology is an information artifact, having the status of a theory which describes the world, similar as physics describes a particular area of the world. With this respect, an ontology about a certain domain of the world can be understood as a hypothesis about the structure and the laws of this domain. It is generally assumed that the objects, considered in this theory, exhibit a mode of existence. Hence, any reasonable theory should be committed to explicate the existence of the considered entities. The study of the most general features of the world is related to theories, which can be applied to any area of the world. Though, there are specialized ontologies, which are related to a particular domain. In this sense one may distinguish various levels of abstraction, as top level ontologies, domain core ontologies, and domain ontologies. Formal ontology transforms philosophical ideas into axiomatic formalizations which are usually missing in the pure philosophical investigations.

3. Artificial Intelligence, Computer Science, and Formal Ontology

An ontology must be represented and specified by expressions of a language. We assume that the general terms in these expressions denote concepts. T. Gruber introduced the notion of ontology into computer science by stipulating that an ontology is an explicit specification of a conceptualization (Gruber 1993). This specification must be expressed in a formal language, and there is a variety of formal specification systems. A main distinction is drawn between logical languages with model-theoretic semantics and formalisms using graph-theoretic notations. A formalized ontology consist of axioms that describe the content of the concepts and relations implicitly. Hence, an ontology - as an information artifact - corresponds to a knowledge base or knowledge system. During the sixties of the 20th century there happened a paradigm shift in Artificial Intelligence, expressed by the slogan “in the knowledge lies the power”. Since this time knowledge representation and knowledge processing became a central topic in artificial intelligence, and these results and methods are integrated into the field of formal ontology. Hence, all methods related to formalizations, and usage of formal languages (logic programs), and deduction mechanisms, are integrated in the field of formal ontology.

A recent development in computer science, the semantic web, influences the field of formal ontology. Formally, RDF (Recource Description Framework), is a formal language, that can be interpreted as a special logical calculus with model theoretic semantics. Various tools, called editors, were developed to implement ontologies. A well-known editor is Protégé which is widely used in many application areas. Such tools are integrated into the framework of formal ontology; they present the applied end of formal ontology.

Another topic, related to artificial intelligence, which is important for formal ontology, is cognitive science, in particular the theory of concepts, as expounded in (Murphy 2004). This field discusses problems of concept formation, and of perception (Mausfeld 2002). Formal ontology supports a revival of Gestalt theory, because this field, in our opinion, is a missing link for understanding various mental-psychological phenomena. Hence, there is an interplay between formal ontology, Gestalt theory, and the philosophy of mind.

4. Logic Methods in Formal Ontology

In this section we consider main aspects of formal logic in formal ontology. 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 itself 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 provides 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 the (relative) truth of the axioms can 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 ones 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.

5. Principles of the General Formal Ontology (GFO)

In this section we give an overview on 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. GFO integrates all aspects of ontology into a unified framework. In the following the basic building blocks of GFO are summarized, and it is made explicit which sources of other sciences are integrated. In this section we expound the main ideas of formal ontology, which integrates the basic facets, described in the preceding sections. Concerning the modes of existence, GFO distinguishes four different ontological regions, called the material one (subdivided into the physical entities, the chemical, and the biological), the psychological region, the socio-systemic region, and the region of ideal entities (as mathematical entities, and subjectively constructed idealized entities).

5.1 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.

5.2 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 is 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.

5.3 Time and Space

Time and space are basic categories that are fundamental in every top level ontology. The GFO approach of time is inspired by Brentano's ideas (1976) on continuum, space and time. Following this approach, chronoids are not defined as sets of points, but as entities *sui generis*. Every chronoid has exactly two extremal and infinitely many inner *time boundaries* which are equivalently called *time-points*. Time boundaries depend on chronoids (i.e. they have no independent existence) and can *coincide*. Starting with chronoids, we introduce the notion of *time region* as the mereological sum of chronoids, i.e. time regions consist of non-connected intervals of time. Time entities, i.e. time-regions and time-points, share certain formal relations, in particular the part-of relation between chronoids and between time-regions, denoted by tpart(x,y) the relation of being an extremal time-boundary of a chronoid, denoted by the relations lb(x,y) (x is left-boundary of y), rb(x,y) (x is right boundary of y, and the relation of coincidence between two time-boundaries, denoted by tcoinc(x,y).

Analogously to chronoids and time boundaries, the GFO theory of space introduces *topoids* with *spatial boundaries* that can coincide. *Space regions* are mereological sums of topoids. To describe the structure of space (or of regions, respectively) we employ the basic relations *spatial part-of*, *boundary-of*, as well as the *coincidence of boundaries*. Formally, we use spart(x,y) x is a spatial part of y, *bd*(x,y), if x is a boundary of y, and *scoinc*(x,y) if two (spatial) boundaries x and y coincide. This approach may be called *Brentano space*, and it is important to understand, that spatial boundaries can be found in a greater variety than point-like time-boundaries: Boundaries of regions are *surfaces*, boundaries of surfaces are *lines*, and boundaries of lines are *points*. As in the case of time-boundaries, spatial boundaries have no independent existence, i.e. they depend on the spatial entity of which they are boundaries.

5.4 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 ones. 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.

5.5 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, (1965), 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), (Gärdenfors 2000). In contrast to top level ontologies as BFO (Spear 2006), and DOLCE (Borgo et al., 2010), the top level ontology GFO , (Herre 2010), includes an ontology of categories, the most important of which are the concepts.

5.6 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. 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, (Peter van Inwagen 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), (Smith 2006). We believe that integrative realism overcomes weaknesses of the type of philosophical realism defended in (Smith 2004).

5.7 Development of Ontologies - A Contribution to Theory Formation

We summarize the basic steps for the development of an ontology, according to the GFO-methodology. An ontology usually is associated to a domain, hence, we must gain an understanding of the domain which is under consideration.

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 Hjorland (2013). 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 (Hjorland 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.*

2. Step: Conceptualisation.

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 sub-step is pertained 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 is 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. Step: Axiomatisation. 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 of the language used, more combinations of given concepts and relations.

A relevant feature of the axiomatisation 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.

5. 8 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. 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 a broad

spectrum of applications in the field of the semantic web. Examples of such applications are presented in (Hoehndorf 2009a,b,c).

(2) Harmonization of concepts are 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 is 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 2009a). Other applications of this kind are presented in (Baumann et al., 2012) on the ontology of time.

6. Future Research

As discussed in the preceding section, there are different types of applications. There are many open problems related to computer science applications, or harmonization of concepts and terms. Though, we restrict in the sequel to the topic of theory formation and modeling, which is - as a research area in ontology - in its initial phase.

Set theory plays the role of core ontology for mathematics, in the sense, that any mathematical notion can be reconstructed within set theory. The integration of set theory into ontology is an unsolved problem. In GFO we build the ontology of sets upon some ideas of D. Lewis (1999) of classes). According to D. Lewis the essence of sets can be reduced to an understanding and interpretation of singletons (sets which exactly one element). Hence, the ontology of sets is derived from an understanding of singletons. In (Herre 2010b) some ideas on this topic are discussed.

There are open problems in the field of data analysis, data interpretation, and data semantics Ontology may contribute to the establishment of a data science, which is currently an urgent problem to be solved, because of the pressing needs to solve problems, related to the so-called big data.

An important topic is the investigation of phenomenal space and time, and the structure of the sense-data spaces. In (Baumann and Herre 2010), the ontology of space in GFO is expounded. It is known that the metrics of the sense data spaces are different (depending of the type of senses), as discussed in the paper on space. It might be an interesting research project to analyse the transformation rules of the mind's cognitive apparatus which translates between the metrics of the different sense data spaces.

Basic problems in economy and society are genuine ontological problems. It turns out that the problems, which the mainstream economical theories face today, forces the need for a new foundation of economical science. Ontology may play here a decisive role in developing and establishing such theories. We hold, that - from an ontological point of view - the Marxist approach is the most important one. Hence, this research line should be taken up and Marxist theories should be further developed. The acknowledge of Marx's Capital, to be included in the UNESCO Memorial of the World Culture, is an encouraging condition for a revival and further development of Marx's theories in general. Such a perspective was already predicted by J.-P. Sartre (Sartre 1999), and is verified today.

Literatur

Aristoteles (1993) Metaphysik, Reclam

Aristoteles (1998) Die Kategorien, Reclam

Baumann, R., Loebe, F., Herre, H. (2012) Ontology of Time in GFO Proceedings of the 7th International Conference on *Formal Ontology in Information Systems*, FOIS 2012, Graz, Austria.

Baumann, R. Herre, H. (2010) Ringo Baumann and Heinrich Herre. The axiomatic foundation of space in GFO. arXiv:1110.5832, http://arxiv.org/abs/1110.5832

Brentano, F. (1976) Philosophische Untersuchungen zu Raum, Zeit und Kontinuum. Felix Meiner Verlag, Hamburg,

Borgo, Stefano, Claudio Masolo (2010) , Ontological foundations of DOLCE. In (Poli 2010), chapter 13, pages 279–295.

Gärdenfors, P. (2000). *Conceptual spaces: The geometry of thought*, A Bradford Book. Cambridge, MA: MIT Press.

Gnoli, C. (2008). Ten Long-Term Research Questions in Knowledge Organization, in: Knowledge Organization, 35(2/3), 137-149.

Gracia, Jorge, J. E. (1999) Metaphysics and its Tasks: The Search for the Categorial Foundation of Knowledge, State University of New York Press, Albany, 1999

Gruber, T.R (1999) A translation approach to portable ontologies. *Knowl Acquisition* 1993; 5: 199-220

Hartmann, N. (1965). Der Aufbau der realen Welt. Walter de Gruyter and Co, Berlin 1965

Hegel, G.W.F. (1971) Werke (insbesondere: *Die Phänomenologie des Geistes*, und *Wissenschaft der Logik*), Suhrkamp

Herre, H, et. al. (2007) . General formal ontology (GFO) – A foundational ontology integrating objects and processes, Report Nr. 8, Onto-Med, IMISE.

Herre, H. (2010a). GFO: A Foundational Ontology for Conceptual Modeling, In: Poli, R. Obrst, L. (ed.) *Theory and Applications of Ontology.* Vol. 2, Berlin: Springer, July 2010.

Herre, H. (2010b). The Ontology of Mereology: An Logical Approach. In: Poli, R. Obrst, L. (ed.) *Theory and Applications of Ontology.* Vol. 1, Berlin: Springer, July 2010.

Herre, H. (2013). Formal ontology and knowledge organization, International Journal of Knowledge Organization

Herre, H. Loebe, F. (2005). A Meta-ontological Architecture for Foundational Ontologies. In: Meersman, R. Tari, Z. (ed.) On the Move to Meaningful Internet Systems 2005: CoopIS, DOA, and ODBASE: Proceedings of the OTM Confederated International Conferences, CoopIS, DOA, and ODBASE 2005, Agia Napa, Cyprus, Oct 31 – Nov 4, 2005 (Part II*). Lecture Notes in Computer Science* Vol. 3761, pp. 1398-1415. Berlin: Springer.

Hjorland, B. (2008) What is Knowledge Organization (KO)? Knowledge Organization, 35 (2008), p. 86-101

Hjorland, B. (2009) Concept Theory. Journal of the American Society for Information Science and Technology,60 (B), 1519-1536, 2009

Hilbert, D. (1918). Axiomatisches Denken. *Mathematische Annalen*, 78:405–415, 3, S. 142-151.

Hoehndorf, R., Loebe, F., Poli, R., Herre, H. Kelso, J. (2008). GFO-Bio: A biological core ontology. *Applied Ontology* Vol. 3(4), pp. 219-227.

Hoehndorf, R. Kelso, J., Herre, H. (2009a). .The ontology of biological sequences. *BMC*

Bioinformatics Vol. 10 (377) 2009

Hoehndorf, R., Ngonga Ngomo, A.-C., Herre, H. (2009b). Developing Consistent and Modular Software Models with Ontologies. In: Fujita, H., Marik, V. (ed.) *New Trends in Software Methodologies, Tools and Techniques* Proceedings of the 8th International Conference, SOMET-2009, 2009, p. 399-412

Hoehndorf, R., Loebe, F., Bacher, J., Backhaus, M., Gregorio Jr., S., Prüfer, K., Visagie, J., Uciteli, A., Herre, H., Kelso, J. (2009c).BOWIKI: an ontology-based wiki for annotation of data and integration of knowledge in biology. *BMC-Bioinformatics* Vol. 10 (Suppl 5):S5

Husserl, E. (1913) Logische Untersuchungen Band 1, Niemeyer, Halle 1913

Husserl, E. (1901) Logische Untersuchungen Bd. 2. Untersuchungen zur Phänomenologie und Theorie der Erkenntnis. Niemeyer, Halle

Ingarden, R. (1964). *Der Streit um die Existenz der Welt I (Existentialontologie)*. Tübingen: Max Niemeyer Verlag.

Inwagen, P. van. (1998). Metaphysics: The Big Questions. Blackwell Publishing Ltd.

Klaus, G. Spezielle Erkenntnistheorie. Prinzipien der wissenschaftlichen Theorienbildung. Deutscher Verlag der Wissenschaften, 1965

Klaus, G. Kybernetik in philosophischer Sicht, Dietzverlag, 1965

Mausfeld, R. (2002) The physicalist Trap in Perception Theory, in: D. Heyer, R. Mausfeld (eds). Perception and the Physical World, Chichester: Wiley

Merril, G. H. (2010). Ontological realism: Methodology or misdirection? *Applied Ontology*, 5:79–108.

Murphy, G. L. (2004). The Big Book of Concepts, Bradford Book, Cambridge Massachusetts

Palchunov, D. E. (2005) Logical Definition of Object Ontology. In: Asian Logic Conference, Novosibirsk, 2005, p. 113-114, ISBN, 5-94356-283-4

Poli, R. (2001) The basic Problem of the Theory of Levels of Reality. *Axiomathes* 2001; 12: 261-283

Poli, R., Michael Healy, and Achilles Kameas, editors. (2010). Theory and Applications of Ontology: Computer Applications. Springer, Heidelberg,

Quine, Willard V.O. (1951). Two Dogmas of Empiricism. In: The philosophical Review 60 (1951), p. 20-43

Ranganathan, S.R. (1965) The Colon Classification (Rutgers series on systems for the intellectual organisation) of information, vol.4) New Brunswick, NJ.

Sartre, J.-P. (1999) Marxismus und Existentialismus, in: Fragen der Methode, rororo (Rowohlt), 1999

Smith, B. (2004) Beyond concepts: Ontology as reality representation. In FOIS, International conference on formal ontology and information systems,73–84, Turin: IOS Press.

Smith, B., W.Ceusters, and R. Temmermann. 2005. Wüsteria. In Proceedings Medical Informatics Europe 2005, Geneva; *Studies in Health Technology and Informatics* 116:647–652.

Smith, B. 2006. From concepts to clinical reality: An essay on the benchmarking of biomedical terminologies. *Journal of Biomedical Informatics*, 39:288–298.

Spear. A.D.. Ontology for the Twenty First Century: An Introduction with Recommendations. IFOMIS, Saarbrücken, Germany, Dec 2006.