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On the Analysis of FORT; arguments, alignment to FOs, and CLIF validation

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Abstract

Foundational relations are formal and generic relations presenting a basic pillar of foundational ontologies (FOs). The employment of these relations in practice has become widely prevalent by means of FOs. However, for the utilization of sole foundational relations, we believe that a basis done exclusively on a FO is unsatisfactory due to (1) the difficulties that modelers face upon selecting a FO for practice, and (2) the fact that no FO incorporates inclusively the basic set of foundational relations in which we are interested. Hence, we have proposed in an earlier work an entity-type-free minimal set of Foundational Ontological Relations Theory (FORT). In this paper, we expound on the two arguments for FORT, compare and elucidate an alignment between FORT's micro-theories and the relation-based content of some FOs, and associate FORT with a CLIF-serialization that validates the consistency of the theory.

Keywords

Foundational Relations, FORT, Foundational Ontologies, Common Logic, CLIF

1. Introduction

Foundational relations are formal and generic relations that play a fundamental role in the ontological foundations of conceptual modeling. These relations have been highly investigated in the applied ontological and philosophical literature, such as the parthood and connection relations in mereological and topological theories.

The practice in foundational relations as a language of primitive relations and rule constraints has shown itself convenient in several application domains, such as contextualizing parthood typologies in cognitive sciences [1], linguistics [2], ontology [3], and conceptual modeling [4]. Depending on the requirements of the intended application domain, the needed foundational relations are specified, (re-)formalized, and (re-)used. For the application of our approach, we are specifically interested in the relations that are imperative for the representation-of and reasoning-over the structural, semantic, and spatial constraints of an entity, across any domain. This comprises modeling the link between; an entity as a whole and its different inseparable parts; an entity as collective whole and the entities that it groups under certain semantics; an entity and its constituents; an entity and the spatial region that locates it; and the spatial constraints among entities. To be applicable on an entity across any domain, this requires that the relations be generic i.e. independent of relata types. Hence, we target the following set of

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foundational relations; parthood, dependence, constitution, membership, and location with the formal properties and relations that are required to characterize them.

Moreover, foundational relations, together with general primitive concepts, form the pillars of foundational ontologies (FOs) aka upper/top-level ontologies. Nowadays, FOs are establishing forward the development of specific (core, domain, and application) ontologies and ontology-driven conceptual models i.e. enhancing the construction of models that are compliant with FOs and their ontological commitments, which guarantees their validation. In addition to that, achieving interoperability between models is reinforced upon the employment of FOs such as in the integration of different ontologies that comply to a unique FO in inter-disciplinary fields. As a consequence, the employment of foundational relations has become widely prevalent by means of FOs, where a unique set of relations is offered and formalized in each.

Although some relations are commonly addressed among FOs, this set varies according to the ontological commitments made by each FO. For instance, a FO that revokes the co-existence of multiple individuals in the same space-time would treat the relation between a constituent and the constituted entity as an identity but not a constitution, and thus rejects the inclusion of constitution within its set of foundational relations. Thus, it is noticed that no FO covers completely the set of foundational relations in which we are interested (1). In addition to that, upon selecting a FO for practice, it is often recognized that modelers do face some complications concerning the complexity of the FO, the obligation to conform to the ontological commitments of the FO, and the concept-hierarchy mappings (2).

Based on the two preceding issues, we believe that for the representation and employment of solely foundational relations in general, and the mentioned set of relations in particular, a basis done exclusively on a FO is unsatisfactory.

Hence, in [5], we have posed our research problem of why not have a theory of pure foundational relations besides large complex FOs. And to overcome this problem, we have proposed an entity-type free theory of a minimal set of foundational ontological relations (FORT). The approach followed for the development of FORT includes a methodology of four steps to be accomplished. In [5], we have successfully achieved the first step; formalizing FORT in first-order logic (FOL) as the expressive logical language for the specification of formal theories such as FOs. For that, we have selected, characterized, and axiomatized the minimal set of relations that establish FORT. In this paper, we first present FORT briefly (Section 2) for the reader to have the formalization available. Then we proceed with the second step of the methodology; expounding the arguments for FORT that derive from the two challenges that modelers face upon using FOs for the sake of foundational relations (Section 3); elucidating an alignment between FORT's micro-theories and the relation-based content of some FOs (Section 4); and associating FORT with a CLIF-serialization as a Common Logic [6] ontology that validates the existence of models for FORT using consistency checks (Section 5). Whereas the third and fourth steps of the methodology are in progress and involve; FORT's translation into a decidable knowledge representation language that supports reasoning and inference services (an SROIQ-DL specification); and its implementation in an ontological language supporting its practices in ontology-driven conceptual modeling tasks (an OWL2-DL ontology).

Therefore, the contributions of this paper are twofold; (a) the positioning and alignment of FORT with respect to some FOs, and (b) the validation of FORT's consistency while providing a CLIF-serialization.

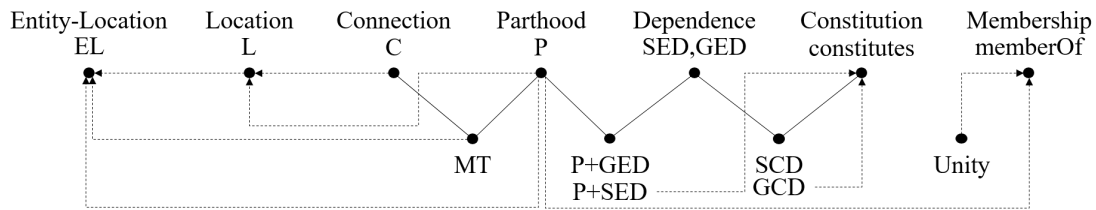


Figure 1: FORT’s relation modules, their interlinks (plain lines) and participation, as axioms in the formalization of other relations (dotted lines).

2. Preliminary work; FORT

In this section, we illustrate briefly the work done around FORT in [5]. FORT is group of intralinked relation micro-theories, also called ontology modules, that are interlinked as shown in figure 1. FORT as a theory presents a minimal set of foundational ontological relations that are free of entity-types. It is intended to aid modelers who aim to use foundational relations in practice, without wanting to commit to a set of entity-types upon using a FO. This is by importing FORT as a language of primitive relations and rule constraints into the user’s model (which represents a certain application using domain-specific categories and links).

In the following, we clarify some characteristics of FORT. First, the notion of intralinked relation micro-theories corresponds to a group of definitions, axioms, and theorems that characterize our view (ontological analysis) of a specific relation. Theoretically, each relation has been thoroughly discussed taking into account its literary ontological and philosophical work. Empirically then, the relation has been formalized by importing, reusing and adapting extant theories according to our ontological analysis and requirements.

Second, the notion of interlinked micro-theories corresponds to links drawn between the relations of each micro-theory using axioms.

Third, the notion of entity-type free corresponds to the theory not committing to specific kinds, aka categories, for the entities participating in the relation; the domain and range of relations. Instead, FORT characterizes formally the relations by normalizing constraints on the relations of the relation upon their identification in practice. This is done by introducing axioms that project restrictions on the types that will be allocated for each relation while used in conceptual models, since the theory’s utilization is intended as a. This makes the theory straightforward to integrate within extant theories, without obliging the compliance to a hierarchy of entity types. Fourth, a basic assumption that FORT makes is to distinguish the parthood relation from membership and constitution. This demarcation is adopted to (a) refrain a philosophical debate on the consideration of these relations as part-whole typologies, (b) delimit the scopes upon which transitivity holds, and (c) advocate for the additional semantics that each relation acquires divergent from one another.

The axiomatization of FORT’s micro-theories is briefly illustrated in the appendix section (without presenting that of imported theories i.e. the closure extensional mereology (CEM), the minimal mereotopology (MT), and Varzi’s location (L) theories).

At this point, one might argue that FORT is just a repository of relations gathered as a grab-bag

ontology. However, FORT offers more than just a repository; (1) positioning FORT concerning the well-known literary work on foundational relations where the analysis and valorization of extant work have been performed; (2) analyzing the requirements in the ontology-driven conceptual modeling context in general, and concerning our motivation in particular, where the selection, re-use, and re-formalization of foundational relations have been rendered; and (3) offering what preceded within a generic context as an entity-type free theory where the significance of FORT lies. We believe that such an approach is not a repository, but a theory.

While a major limitation of the approach is in its assumption of being atemporal, the forte contribution points of FORT are twofold. First, the relations being generic and entity-type free offering modelers wide semantics of primitive relations without obliging primitive concepts. Second, the selected set of relations being ample for representing the internal structure, spatial conditions, and interrelations between entities as a minimal, yet inclusive, group of imported and formulated micro-theories of relations.

3. Arguments for FORT

In this section, we expound on the arguments for FORT that derive from two challenges (issues introduced in section Section 1) faced by modelers employing FOs for with the aim to use foundational relations. In particular, we focus on the selected set of relations in which we are interested. It is important to point out that the two defended arguments promote the need for FORT, but do not make assumptions of drawbacks or shortcomings on extant FOs, nor do they argue for eliminating the practice on existing FOs and their corresponding conveniences. The employment of FORT is an option in the conceptual modeling tasks that do not seek the adoption of a category hierarchy but only the utilization of foundational relations.

The difficulties upon the adoption and employment of a FO:

The first difficulty is the responsibility that a FO choice incorporates towards understanding the different ontological and philosophical assumptions made in each FO. With the numerous FOs available today, the modeler having to choose a FO for practice has to understand several points; what does each FO offer differently from one another? what are the theoretical modeling decisions made in each FO, i.e. the ontological commitments that correspond to the world view it acquires? how are these ontological commitments empirically translated into formalizations? Performing such a comparison between FOs is a difficult task since most differences occur at a high meta-physical level which requires deep philosophical understanding. After having this comparison, the modeler has to elect a FO for practice according to the needs of the application domain. This involves answering the following; how can the modeling dilemmas present in the application domain be represented in each FO? how are these representations different, and what are the conveniences offered by each? Only if the modeler can answer all these questions, that necessitate massive work and time efforts, then the proper justification of the choice of FO can be made.

The second difficulty is the entire commitment to the assumptions made in the chosen FO regarding its world-view. Upon employing a FO, the modeler is committed to its view on the elements of reality that is wholly interpreted in its formalization. This can be problematic for the modeler when the modeling dilemma ought to be modeled, cannot be fully represented

by the chosen FO due to the fact that a specific assumption made by it, rejects this view in the dilemma. In case the assumption in the FO is ignored, the representation will yield in contradicting semantics. And in case all assumptions are complied to, then the representation of the dilemma is not fully achieved. Knowing that the list of ontological commitments varies from one FO to another, one might want to comply with one assumption from one FO e.g. BFO's [7] reductionist view (rejects for the co-existence of two entities in the same space-time location), and another assumption from another FO (that the first, BFO, rejects) e.g. DOLCE's [8] parthood theory (general extensional mereology GEM) to solve the modeling dilemma he has. This representation is not plausible, and the modeler needs thus to presuppose the requirements of the modeling problem in order to make the best choice of FO with the least missing representations.

The third difficulty is the obligation to adhere to the categories-hierarchy of the chosen FO. This does not only oblige modelers to map the domain-specific types (aka kinds or categories) in their models to the top-level categories in the chosen FO, but also to comply to the constraints that each type acquires. For example, the category "Non-Agentive-Physical-Object" in DOLCE is disjoint from the category "Amount-of-Matter", and requires that any instance of the former be generically constantly constituted by an instance of the latter by the axioms characterizing both categories. Thus, all categories that are mapped to any of the preceding two, will acquire additional inherited axioms and semantics that the modeler shall comply with.

Thus, several obstacles arrive with FOs in general, and with the commitment to category hierarchies in particular. If the aim behind using a FO is foundational relations, then why not have a relation-centered approach and ignore any taxonomic category axioms?

No FO incorporates inclusively the specified set of foundational relations:

In this argument, we highlight an issue that is not (yet) handled in extant FOs. There is currently no FO that incorporates the intended foundational relations altogether; parthood, dependence, constitution, membership, and location. We elaborate on our claim by addressing some FOs.

BFO does not (and cannot) express constitution due to its reductionist view. BFO is a realist ontology capturing the world as (multiple) particular perspectives of reality i.e. possibly multiple instantiations of the same particular individual. For constitution, BFO regards the entities participating in a constitution relation, e.g. the vase and the clay, as the same spatio-temporal individual that instantiates different universals at the same space-time location i.e. an identity relation instead. Such an argument is added to BFO's formalization using an axiom that prevents two material entities from occupying the same spatial region unless they coincide i.e. the relations collapse to an identity. Now if constitution is to be represented in BFO, then it will be a relationship taking place between an individual and itself as an instance of two different universals i.e. individual ID1 as an instance of a statue and the same ID1 as an instance of clay. This thus requires the fact that individual ID1 be instantiating two classes at the same time instance t . Let's say BFO succeeds in representing such restrictions on a constituted relation. What about the specificity vs generality of this constitution? In other words, is it a constitution that is applied specifically to these to individuals? Or is it a constitution that takes place between any instance of the category of the constituent entity (any instance of clay) and any of the constituted entity (any instance of statue)? In the latter case, the representation of constitutional dependence (generic) between the constituent and the constituted entity, which is

an important axiom in the characterization of the constitution relation, will still be unachievable. This is because constitutional dependence requires the two class types to be disjoint to ensure that the causal existential connection between instances of the classes comes to an end. Thus, constitution remains to be problematic for BFO.

DOLCE, on the other hand, does not explicitly define a locative relation nor does it adopt a specific location theory such as that of Varzi. Instead it offers locative representations via qualities and quales as will be explained in section 4. In view of such a comprehensive treatment of relations, membership is not (yet) covered within DOLCE's specification. Although in the earlier analysis of building DOLCE, in [9] which presented a preliminary work for DOLCE as a systematic methodology for selecting and defining some general ontological categories and relations, the authors have already considered the treatment of the membership relation. The analysis has been induced in terms of parthood in the spirit of the analysis presented in [10], with an interpreting a unifying relation that binds all members of a whole (collective/aggregate) together and a maximality constraint on the members with respect to his relation. However, no consideration of membership has (yet) been shown in DOLCE.

Similar to DOLCE, with some differences in their treatment of regions, UFO does not integrate a theory of location relations. Instead it presents an entity-type based approach of *attributes* and *attribute value spaces* following [11]. Such an approach can cover the locative representation between regions, and between entities (i.e. material ones) and regions. However, what about representing locative relations between entities that are not spatial regions? For example, consider two entities that occupy a shared spatial region. On the one side, these entities are not parts and do not share any parts i.e. mereology is insufficient. On the other side, these entities are not exactly located in the same spatial region i.e. the "being exactly located at" primitive of the Varzi' location theory is also insufficient. There is a need for a module other than mereology or basic region locations, such as containment [12] and inclusion theories [13], for clarifying and determining the spatial information embodied between entities in ontologies and enhancing their automatic reasoning.

Thus, each of the tackled FOs lacks some relation(s) due to some of its ontological commitments. If the intended relations are specified, then why not have an inclusive relation theory that encompasses the desired relations entirely?

4. Aligning FORT to some FOs

In this section, we align and elucidate a relation-based comparison between each micro-theory in FORT and the corresponding consideration of the relation made in the FOs; BFO, DOLCE, and UFO, summarized in table 1. The FOs that we inspect are those to which our theory presents high similarities.

4.1. Ontological dependence

The dependence relation is generally defined in terms of an existence primitive relation, also referred to as "being present". The existence relation is pretty similarly presented in all FOs; *existsAt* in BFO, *PRE* (being present at) in DOLCE as binary predicates between an entity and an instance of time, and *ex* in UFO as a unary predicate due to a single time slice formalization.

Table 1

A relation-based comparison between the micro-theories in FORT and the corresponding consideration of the relations in the FOs; BFO, DOLCE, and UFO.

Foundational Relations	FORT	BFO	DOLCE	UFO
existential dependence	SED & GED	(s-depends-On)	YES	YES
parthood	CEM theory	own mereology	GEM	GEM
parthood & dependence	componentOf & elementOf	-	(possible)	(possible)
parthood & connection	MT theory	-	-	-
EntityToRegion Location	Location _{Varzi}	(occupies-SR)	(qualities)	(attributes)
EntityToEntity Location	EL	LocatedIn	-	-
Membership	memberOf (+U)	memberOf (-U)	-	memberOf
Constitution	constitutes	-	YES	YES
Constitutional dependence	SCD & GCD	-	YES	YES

In BFO; ontological dependence is introduced in the form of entity types that are dependent on other entity types i.e. *SpecificallyDependentContinuants* such as: qualities, functions, roles, and dispositions, and *GenericallyDependentContinuants*. This dependence is carried out via relation *s-depends_on* has as a domain a *SpecificallyDependentContinuant* and as a range; an *IndependentContinuant* or *Process* in case of a *one-sided s-dependence*, or a *DependentContinuant* in case of a *reciprocal s-dependence*.

In UFO, in addition to existential dependence $ed(x, y)$ and independence $ind(x, y)$, functional dependence is also studied in its generic $gfd(\Phi, \Psi)$ and individual $ifd(x, \Phi, y, \Psi)$ -defined in terms of gfd - forms according to the treatment of functional parts by Guizzardi in [4].

DOLCE introduces two types of dependence relations; specific between particulars $SD(x, y)$ or universals/properties $SD(\Phi, \Psi)$, and generic between universals/properties $GD(\Phi, \Psi)$. Using these two types, other forms are also defined e.g. one-sided and mutual dependencies.

Similar to DOLCE's account for dependence, FORT analysis two types of the relation, namely existential dependence in two forms, specific $SED(x, y)$ and generic $GED(x, y)$ within a non-modal approach. This is less similar to UFO's approach, and completely dissimilar from that of BFO which does not meet our interpretation as explained in section 3.

4.2. Parthood

FORT adopts CEM, while DOLCE and UFO both adopt GEM, and BFO constructs its own mereology within its continuant part of relation.

FORT further accounts the combination of parthood with dependence to introduce the notion of inseparable parts (essential and mandatory); elements and components. This is plausible in DOLCE since the primitive relations (parthood and specific/generic existential dependence) exist. In UFO, it is feasible using the existential dependence relation to introduce essential parts (aka elements in FORT) but not mandatory parts (aka components in FORT). However, UFO does define dependent parts as components using the $componentOf(x, y)$ relation that is proper parthood $PP(x, y)$ accompanied with a restriction on the individual functional dependence of the whole on the part $ifd(x, x', y, y')$.

For the mereotopological theoretical aspect, none of the considered FOs imports the connection topological theory, whereas FORT imports minimal mereotopology i.e. the primitive connection relation with its corresponding topological predicates.

4.3. Location

Since locative relations in FORT are divided into three types, we investigate according to each type, the similar relations in each of the studied FOs.

- region-to-region locative relations: Without committing to a region entity type, FORT suggests the use of the primitive parthood relation *part – of* to express mereotopological representations between entity types that can be regions. This is similar to BFO’s utilization of its own mereological relation *continuantPartOf* between spatial regions, and DOLCE’s and UFO’s use of the primitive mereological relation *PartOf*.
- entity-to-region locative relations: In FORT, we import Varzi’s location theory [14], which in turn links to the imported mereotopological theory. While BFO uses the *occupiesSpatialRegion* relation to express the spatial region that an independent continuant entity is acquiring, both DOLCE and UFO adopt different views for location representations via qualities (in DOLCE) and attributes (in UFO). In DOLCE, in terms of quality types and quales, location can be described as a scenario encompassing; (a) a quality type, which in the case of expressing a location, is the spatial location of an entity e.g. *SL1* as a instance of the class *SpatialLocation* which is a subclass of *PhysicalQuality*, which is a subclass of *Quality*, (b) a quale i.e. the spatial region which the entity is covering e.g. *SR1* which is an instance of the *SpatialRegion* which is a subclass of *PhysicalRegion*, which is a subclass of *Region*, and (c) a relation *Qlt* that links both the quality type and its corresponding quale i.e. links *SR1* to *SL1*, at a specific time. Whereas in UFO, a similar representation is done using attributes and attribute value spaces.
- entity-to-entity locative relations: these are expressed in FORT using the entity location *EL* primitive relation indicating ”located at/on/in”. BFO in turn uses a simple primitive relation *located – In* between two independent continuants that are not spatial regions, while both DOLCE and UFO do not account for such a representation.

4.4. Membership

FORT examines membership *memberOf(x, y)* as a primitive relation that is defined in terms of ground axioms with the characterization of its whole entity. Although FORT does not account for entity types, it requires restriction on the range of the membership relation to be unified $U_{R_i}(y)$, through its members, by a unification relation $R_i(x, x)$. The axiomatization provided in FORT is similar to that in BFO except that BFO uses a class type *AggregateEntity* to characterize the whole while FORT does not, and BFO does not oblige the binding of all members according to a similarity constraint i.e. unifying relation. UFO also provides a membership primitive *memberOf(x, y)* that holds between an object and a collection following the preliminary analysis in [15] and [16]. However, for DOLCE, membership is not (yet) considered although the notion has been addressed in the preliminary studies for ontological distinctions as mentioned in section 3.

4.5. Constitution

FORT treats constitution in a very similar manner to that in DOLCE and UFO. Using a constitution primitive $constitutes(x, y)$ ($K(x, y)$ in DOLCE, and $constitutedBy(y, x)$ in UFO) along with defining specific and generic constitutional dependencies $SCD(x, y)/GCD(\Psi, \Phi)$. However, in contrary to DOLCE's concept *AmountOfMatter*, FORT does not restrict types but applies additional axiomatization on the relation. For BFO, as discussed in section 3, constitution is not regarded.

5. FORT as a CL-ontology

In this section, we associate the theory with another logical language; a CLIF-serialization as a Common Logic (CL) [6] ontology that validates the existence of models for FORT using consistency checks.

CL, which is an extension of KIF (Knowledge Interchange Format), is a logical language based on FOL, with the purpose of standardizing syntax (e.g. "CLIF"; the Common Logic Interchange Format) and semantics for information interchange and transmission. CL is used in ontological theories as a formal language tool to prove the consistency of a theory by validating the existence of model(s) M for a theory T . For example, BFO¹ and some of DOLCE's modules² are encoded in CLIF. In addition to FOs, an open-access repository of first-order theories "CoIore" is implemented as CL-ontology modules³ such as mereology.

5.1. A CLIF-serialization of FORT

Considering that FORT is a group of interlinked ontology modules that imports and reuses some extant theories from the literature, firstly we import those that are already encoded and available online at the "CoIore" repository. These are; the CEM mereological theory⁴, the MT mereotopological theory along with the basic connection topological theory⁵, Varzi's Location theory⁶, and their corresponding definitions. We modified some files e.g. the mereological definitions file to account for additional definitions e.g. overcross, undecross, etc, the location root file to remove region axioms, etc.

Secondly, we initiate the serialization of FORT's micro-theories in the sense of "what-comes-first?" i.e. starting by the basic primitive relations that do not necessitate the use of other primitives, and passing to relations that import other relations in their modules. The full CL formalization of the theory is available online on GitHub repository; FORT.

In the process of encoding the CL ontology of FORT, we face some limitations in the language's syntax. In the following, we identify the issue, locate it in the theory, and propose a solution to dealing with it.

What is the issue? Since FORT is an entity-type free theory, then it's FOL formalization

¹<https://github.com/BFO-ontology/BFO-2020/tree/master/21838-2/common-logic>

²<https://github.com/gruninger/colore/tree/master/ontologies>

³<https://github.com/gruninger/colore/tree/master/ontologies>

⁴https://raw.githubusercontent.com/gruninger/colore/master/ontologies/mereology/cem_mereology.clif

⁵https://raw.githubusercontent.com/gruninger/colore/master/ontologies/combined_mereotopology/mt.clif

⁶https://raw.githubusercontent.com/gruninger/colore/master/ontologies/location_varzi/L_location.clif

comprises mostly variables quantifying over binary predicates (aka relations) without defining unary ones that represent entity types. However, in cases where restrictions on relation types are crucial for the characterization of a relation, we have used unary predicates (e.g. Ψ, Φ, φ) that resemble entity types. More precisely, these are functions that quantify over a list of entity types that the modeler or the user in application would have. As expressed earlier, the practice of FORT is intended as a relation theory to be imported within the user's application (which is a complete model of concepts and relations) to add semantics and rule constraints. This strategy of dealing with unary predicates that range over a finite set of universals is inline with that proposed by the Common Logic working group ⁷, and followed by DOLCE, as follows: $\exists\varphi(\varphi(x))$ corresponds to $\bigvee_{\Phi \in \Pi}(\Phi(x))$ and $\forall\varphi(\varphi(x))$ corresponds to $\bigwedge_{\Phi \in \Pi}(\Phi(x))$ where Π refers to the finite list of concept names in the ontology. According to such a treatment, it is possible to express existential and universal quantification on universals in DOLCE. However, FORT does not provide a hierarchy of concepts, thus asserting ranging predicates on a set of universals Π is not possible. The same issue also applies on quantifying over binary predicates that resemble relations.

Where is the issue located in FORT? We track this issue by identifying the definitions and axioms in FORT that use such a quantification over unary/binary predicate names. These are: (a) the use of a universal quantifier on concepts in the generic existential dependence relation, and (b) the use of existential quantifiers on the unifying relations in the definition of a unified entity.

How can the issue be resolved? We elucidate a possible strategy to resolve this issue. If we quantify over unary/binary predicate names in CLIF serializations, the syntax will be violated. If we withdraw the usage of these predicates as ranging over finite sets, the expressive power of some relations in FORT drops. The most suitable strategy is to consider these predicates (Ψ, Φ, φ, R_i) as functions that themselves range over unary and binary predicates and do not need quantification. In other words; the usage of $\varphi(x)$ shall correspond to a definition of φ as $\varphi(x) = \exists\Phi(\Phi \in \Pi \wedge (\Phi(x)))$ in which in practice will be encoded as $\varphi(x) = C_1(x) \vee C_2(x) \vee \dots \vee C_n(x)$ where each of $C_i(x)$ will correspond to a category in the user's model. Similarly for role names, the usage of $R_i(x)$ shall correspond to the union of all unifying relations, thus can be considered as the parent of all unification relations. The sole drawback of this solution is that it adds to modelers the effort of adding some definitions to their models to maintain the validity and consistency of the theory, while achieving the intended expressive power. The sole difference in comparison to DOLCE's strategy lies in the finite set Π where DOLCE restricts the elements of its set to its defined category types, while FORT offers the possibility for the user to specify the user-categories that the predicates will range over.

5.2. Automatic translations and consistency checks

Besides a CLIF serialization, we performed an automatic translation of FORT into the LADR syntax of Prover9 which is the format required by Prover9 and Mace4, and to the TPTP format, to offer multiple serializations of CL.

⁷cl.tamu.edu

For this translation, several tools exist such as the CLtools repository⁸, which has been previously adopted by⁹ for a theory’s translation to Ladr syntax. However, no maintenance of the tool or resolving of its issues has been carried out in the last decade. Another tool is the macleod program¹⁰ which consists of python scripts that can; translate a CLIF file to tptp and ladr formats; extract an OWL approximation of a clif ontology/module; verify the logical consistency of a clif ontology; verify the non-trivial logical consistency of a CLIF ontology; and prove theorems/lemmas that encode intended consequences of an ontology or module. So, we adopted the macleod program, in which we had to modify some configuration files and adapt some scripts, to build TPTP and Prover9 translations for each ontology module.

As for running consistency checks, we used the ”darwin¹¹” consistency checker in “The Heterogeneous tools set” [17] (Hets)¹² to check the consistency of each ontology module, followed by the full FORT theory, yielding in consistent results.

6. Conclusion

In this paper, we have illustrated our previous work on FORT [5] that corresponds to the first step of FORT’s methodology, as a preliminary for this paper’s presentation. Then we proceeded forward to accomplish the second step of the methodology where the contributions twofold. The first contribution is the positioning and alignment of FORT concerning some selected FOs. To do so, we defended and expounded two arguments for FORT (Section 3); (a) the difficulties that modelers encounter upon adopting and employing a FO; and (b) the fact that no FO (yet) incorporates inclusively the specified set of foundational relations (parthood, dependence, constitution, membership, and location with the formal properties and relations that are required to characterize them) with elaborating on those relations that are not handled each FO. In addition, we elucidated a relation-based comparison between each module in FORT and its corresponding aligned relation in each of the selected FOs, to which FORT presents high similarities (Section 4). The second contribution is the validation of FORT’s consistency while providing a CLIF-serialization, translating into TPTP and Prover9 formats, and performing consistency checks to each module and to the full theory (Section 5).

For our future work, we plan to the next steps of the methodology; a decidable knowledge representation language formalization that supports reasoning services i.e a DL-SROIQ formalization; and an OWL2-DL lite implementation of FORT. Such an approach is in line with some approaches in the Semantic Web community which advocate that re-usability is enhanced by eliminating domain/range constraints. Providing such an OWL ontology of relations (FORT-ontology) serves as an ontological tool offering a language of primitive relations and rules, and enhances and facilitates ontology-driven conceptual modeling tasks.

⁸<https://github.com/cmungall/cltools>

⁹<http://www.cs.toronto.edu/~torsten/DCT-BCont/>

¹⁰<https://github.com/thahmann/macleod>

¹¹<http://combination.cs.uiowa.edu/Darwin/>

¹²Hets is a parsing, static analysis and proof management tool incorporating various provers and different specification languages. It can be used either in its web-based interface <http://rest.hets.eu/> or installed it in a Docker container following the instructions <http://hets.eu/>

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A. FORT's micro-theories

A.1. Ontological dependence

$$\forall(x, y)SED(x, y) =_{df} \forall t(E(x, t) \rightarrow E(y, t)) \wedge \neg(x = y) \wedge \exists tE(x, t) \quad (\text{Dd1})$$

$$(\forall x, y, z)SED(x, y) \wedge SED(y, z) \rightarrow SED(x, z) \quad (\text{Dt1})$$

$$\forall(\Phi, \varphi)GED(\Phi, \varphi) =_{df} \forall x, t((\Phi(x) \wedge E(x, t)) \rightarrow \exists y(\varphi(y) \wedge E(y, t))) \wedge \exists x, t(\Phi(x) \wedge E(x, t)) \wedge \neg \exists z(\Phi(z) \wedge \varphi(z)) \quad (\text{Dd2})$$

$$\forall(\Phi, \varphi, \alpha)GED(\Phi, \varphi) \wedge GED(\varphi, \alpha) \wedge \neg \exists x(\Phi(x) \wedge \alpha(x)) \rightarrow GED(\Phi, \alpha) \quad (\text{Dt2})$$

Where Φ and φ are variables that range over universal concepts i.e. correspond to $\Phi = \bigvee_{\Psi \in \Pi} (\Psi(x))$ where Π refers to the finite list of concept names in the ontology.

A.2. Parthood

$$(\forall x, y)ComponentOf(x, y) =_{df} P(x, y) \wedge GED(\Phi(y), \Psi(x)) \quad (\text{Pd1})$$

$$(\forall x, y, z)ComponentOf(x, y) \wedge ComponentOf(y, z) \rightarrow ComponentOf(x, z) \quad (\text{Pt1})$$

$$(\forall x)\neg ComponentOf(x, x) \quad (\text{Pt2})$$

$$(\forall x, y)ComponentOf(x, y) \rightarrow \neg ComponentOf(y, x) \quad (\text{Pt3})$$

$$(\forall x, y)ComponentOf(x, y) \rightarrow PP(x, y) \quad (\text{Pa1})$$

$$(\forall x, y)ComponentOf(x, y) \rightarrow \exists z(P(z, y) \wedge \neg O(z, x)) \quad (\text{Pt4})$$

$$(\forall x, y)ElementOf(x, y) =_{df} P(x, y) \wedge SED(y, x) \quad (\text{Pd2})$$

$$(\forall x, y, z)ElementOf(x, y) \wedge ElementOf(y, z) \rightarrow ElementOf(x, z) \quad (\text{Pt5})$$

$$(\forall x)\neg ElementOf(x, x) \quad (\text{Pt6})$$

$$(\forall x, y)ElementOf(x, y) \rightarrow \neg ElementOf(y, x) \quad (\text{Pt7})$$

$$(\forall x, y)ElementOf(x, y) \rightarrow PP(x, y) \quad (\text{Pa2})$$

$$(\forall x, y)ElementOf(x, y) \rightarrow \exists z(P(z, y) \wedge \neg O(z, x)) \quad (\text{Pt8})$$

A.3. Entity-to-entity location:

$$(\forall x)EL(x, x) \quad (\text{ELa1})$$

$$(\forall x, y, z)(EL(x, y) \wedge EL(x, z) \rightarrow EL(x, z)) \quad (\text{ELa2})$$

$$(\forall x, y)(P(x, y) \rightarrow EL(x, y)) \quad (\text{ELa3})$$

$$(\forall x, y, z)(P(x, y) \wedge EL(y, z) \rightarrow EL(x, y)) \quad (\text{ELt1})$$

$$(\forall x, y, z)(EL(x, y) \wedge P(y, z) \rightarrow EL(x, y)) \quad (\text{ELt2})$$

$$(\forall x, y, z)(EL(x, y) \wedge L(y, z) \rightarrow WL(x, z)) \quad (\text{ELt3})$$

$$(\forall x, y, z, w)(EL(x, y) \wedge L(x, z) \wedge L(y, w) \rightarrow P(z, w)) \quad (\text{ELt4})$$

A.4. Membership

$$(\forall x)\neg memberOf(x, x) \quad (Ma1)$$

$$(\forall x, y)memberOf(x, y) \rightarrow \neg memberOf(y, x) \quad (Ma2)$$

$$(\forall x, y)memberOf(y, x) \rightarrow \exists t, m_1, m_2(m_1 \neq m_2 \wedge E(x, t) \wedge memberOf(m_1, x) \wedge memberOf(m_2, x)) \quad (Ma3)$$

$$(\forall x, p, y)memberOf(y, x) \wedge PP(p, x) \rightarrow \exists o(memberOf(o, x) \wedge O(o, p)) \quad (Ma4)$$

$$(\forall x, y)memberOf(x, y) \rightarrow (PP(x, y) \wedge \forall m(memberOf(m, y) \rightarrow x = d \vee \neg O(m, x))) \quad (Ma5)$$

$$(\forall x, y)memberOf(y, x) \rightarrow (\forall w(O(w, x) \leftrightarrow \exists m(memberOf(m, x) \wedge O(w, m)))) \quad (Ma6)$$

$$(\forall x, y)R_i(x, y) \rightarrow R_i(x, x) \wedge R_i(y, y) \quad (Ra1)$$

$$(\forall x, y)R_i(x, y) \rightarrow R_i(y, x) \quad (Ra2)$$

$$(\forall z)\mathcal{U}_{R_i}(z) =_{df} \forall r(R_i(r, r) \rightarrow P(r, z)) \wedge \forall m(O(m, z) \leftrightarrow \exists r(R_i(r, r) \wedge O(m, r))) \wedge \forall a, b(R_i(a, a) \wedge R_i(b, b) \wedge P(a, z) \wedge P(b, z) \rightarrow R_i(a, b)) \quad (Rd1)$$

$$(\forall x, y)memberOf(y, x) \rightarrow \exists i(\mathcal{U}_{R_i}(x) \wedge (\forall t(exists(x, t) \rightarrow \mathcal{U}_{R_i}(x))) \quad (Ma7)$$

$$(\forall x, y, w, z)memberOf(x, y) \wedge memberOf(w, z) \wedge \exists i(\mathcal{U}_{R_i}(y) \wedge \mathcal{U}_{R_i}(z)) \rightarrow y = z \quad (Mt1)$$

A.5. Constitution

$$(\forall x)\neg constitutes(x, x) \quad (Ca1)$$

$$(\forall x, y)constitutes(x, y) \rightarrow \neg constitutes(y, x) \quad (Ca2)$$

$$(\forall x, y, z)constitutes(x, y) \wedge constitutes(y, z) \rightarrow constitutes(x, z) \quad (Ca3)$$

$$(\forall x, y)constitutes(x, y) \rightarrow \exists t(E(x, t) \wedge E(y, t)) \quad (Ca4)$$

$$(\forall x, y, z)constitutes(x, y) \wedge P(z, y) \rightarrow \exists x'(P(x', x) \wedge constitutes(x', z)) \quad (Ca5)$$

$$(\forall x, y)SCD(x, y) =_{df} \exists t E(x, t) \wedge \forall t(E(x, t) \rightarrow constitutes(y, x)) \quad (Cd1)$$

$$(\forall \Phi, \Psi)GCD(\Phi, \Psi) =_{df} \neg \exists z(\Phi(z) \wedge \Psi(z)) \wedge \forall x(\Phi(x) \rightarrow \exists t E(x, t)) \wedge \forall x, t(\Phi(x) \wedge E(x, t) \rightarrow \exists y(\Psi(y) \wedge constitutes(y, x))) \quad (Cd2)$$

$$(\forall x, y)SCD(x, y) \rightarrow SED(x, y) \quad (Ct1)$$

$$(\forall \Phi, \Psi)GCD(\Phi, \Psi) \rightarrow GED(\Phi, \Psi) \quad (Ct2)$$

$$(\forall x, y, z)SCD(x, y) \wedge SCD(y, z) \rightarrow SCD(x, z) \quad (Ct3)$$

$$(\forall \Phi, \Psi, \varphi)GCD(\Phi, \Psi) \wedge GCD(\Psi, \varphi) \wedge \neg \exists z(\Phi(z) \wedge \varphi(z)) \rightarrow GCD(\Phi, \varphi) \quad (Ct4)$$

$$(\forall x, y, \Phi, \Psi)constitutes(x, y) \wedge \Phi(x) \wedge \Psi(y) \rightarrow GCD(\Psi, \Phi) \quad (Ca7)$$

$$(\forall x, y)constitutes(x, y) \rightarrow \forall z(P(z, x) \rightarrow ElementOf(z, x)) \quad (Ca8)$$