Merging the DOLCE and PSL Upper Ontologies

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Abstract: In this paper, we examine the relationships between the axiomatization of participation in two upper ontologies, the Process Specification Language (PSL) and the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE). We discuss the obstacles faced to formalize the relationships between these ontologies and provide an overview of the methodology undertaken to merge the ontologies together. We introduce new ontologies that serve to bridge the PSL and DOLCE ontologies together to allow us to specify the mappings between them. We illustrate how ontology verification is used to show faithful interpretations between the two upper ontologies.

1 INTRODUCTION

In order to understand how two ontologies are related to each other, there is a need to explicitly identify the potential relationships between them, and we cannot understand such relationships without analyzing the axioms of the ontologies. In this paper, we explore the relationships between two upper ontologies – the Process Specification Language (PSL) and the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE). Our objective is to determine whether one upper ontology can be interpreted in the other by using techniques from ontology verification to examine the model-theoretic properties of both ontologies. In particular, we examine how the theories found in DOLCE can be mapped to the PSL ontology by using existing ontologies found in the COmmon Logic Ontology REpository (COLORE), and then discuss the steps needed to *bridge* these ontologies together.

With respect to ontology mapping, the research community is often interested in determining whether two *contextually equivalent* ontologies contain the same, or similar, axioms and descriptions of concepts. The intent of ontology mapping is to make semantic matches between the ontologies and to utilize these matches to aid us in reasoning tasks (Kalfoglou and Schorlemmer, 2005). Ontology merging allows the creation of a new ontology from two, possibly overlapping, ontologies (Euzenat and Shvaiko, 2007; Choi et al., 2006). Additionally, in this work, we utilize ontology mapping along with ontology merging to identify similarities and conflicts between the ontologies (Choi et al., 2006).

Our approach to ontology mapping is based on ontology verification, which is concerned with the relationship between the intended models of an ontology and the models of the axiomatization of the ontology. In particular, the models of an ontology are characterized up to isomorphism and then shown to be equivalent to the intended models of the ontology. The objective is the construction of the models of one ontology from the models of another ontology by exploiting the metatheoretic relationships (such as faithful interpretation and definable equivalence) between these ontologies and existing theories in COLORE.

In this paper, we begin by examining the fundamental ontological commitments of the DOLCE and PSL ontologies with respect to the notion of participation. We selected these two ontologies because they appeared to have several commonalities in their axiomatizations of time, process, and participation. However, when we examine the fundamental ontological commitments of these ontologies, we can identify two major obstacles to their integration – they differ on their time ontologies (time points vs. time intervals) and they make different assumptions about how objects participate in activity occurrences. We introduce sets of ontologies that combine both time points and intervals, and which can serve as a bridge between the time ontologies of DOLCE and PSL. We also extend the PSL ontology with new axioms regarding the notion of participation. Figure 1 illus-

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trates the bridges that are created to formalize the relationships between the DOLCE and PSL ontologies. Finally, we show that the resulting extensions of PSL can faithfully interpret the DOLCE ontology, with an emphasis on the semi-automatic verification of these ontologies.

2 ONTOLOGY MERGING THROUGH VERIFICATION

Two key techniques used in this paper are ontology mapping and the design of ontologies through the merging of existing ontologies. In this section, we discuss the notion of ontology verification and how it is used to support ontology mapping. We also review existing ontology merging techniques and discuss how these are related to our approach.

2.1 Ontology Verification

Verification is concerned with the relationship between the intended models of an ontology and the models of the axiomatization of the ontology[1]. In particular, we want to characterize the models of an ontology up to isomorphism and determine whether or not these models are equivalent to the intended models of the ontology. In practice, the verification of an ontology is achieved by demonstrating that it is equivalent to another logical theory whose models have already been characterized up to isomorphism. We therefore need to understand the different relationships among logical theories, which will also lead us to specify the mappings between ontologies.

A fundamental property of an ontology is the range of concepts and relations that it axiomatizes. Within the syntax, this is captured by the notion of the signature of the ontology. The signature $\Sigma(T)$ of a logical theory T is the set of all constant symbols, function symbols, and relation symbols that are used in the theory. The simplest relationships between logical theories are the different notions of extension, in which the signature of one theory is a subset of the signature of another theory. Let T_1, T_2 be two first-order theories such that $\Sigma(T_1) \subseteq \Sigma(T_2)$. We say that T_2 is an *extension* of T_1 iff for any sentence $\sigma \in \mathcal{L}(T_1)$,

$$\text{if} \quad T_1 \models \sigma \quad \text{then} \quad T_2 \models \sigma.$$

[1]A first-order ontology is a set of first-order sentences (axioms) that characterize a first-order theory, which is the closure of the ontology's axioms under logical entailment. In the rest of the paper we will simply drop the term first-order and assume ontologies and theories to be first-order.

T_2 is a *conservative extension* of T_1 iff for any sentence $\sigma \in \mathcal{L}(T_1)$,

$$T_2 \models \sigma \quad \text{iff} \quad T_1 \models \sigma.$$

T_2 is a *non-conservative extension* of T_1 iff T_2 is an extension of T_1 and there exists a sentence $\sigma \in \Sigma(T_1)$ so that

$$T_1 \not\models \sigma \quad \text{and} \quad T_2 \models \sigma.$$

Non-conservative extension plays a key role in COLORE. Ontologies within the repository are organized into sets of ontologies with the same signature known as *hierarchies*. The set of ontologies within a hierarchy are ordered by non-conservative extension; an ontology is a root theory of hierarchy if it is not extended by any other ontology within the same hierarchy.

If the logical theories have different signatures, there is a range of fundamental metalogical relationships which are used in ontology verification. All of them consider mappings between the signatures of the theories that preserve entailment and satisfiability. The basic relationship between theories T_A and T_B is the notion of *interpretation*, which is a mapping from the language of T_A to the language of T_B that preserves the theorems of T_A (Enderton, 1972). The interpretation is *faithful* if the mapping also preserves the satisfiable sentences of T_A.

One notion of equivalence among theories is *mutual faithful interpretability*, that is, T_1 faithfully interprets T_2 and T_2 faithfully interprets T_1. An even stronger equivalence relation is that of logical synonymy: Two ontologies T_1 and T_2 are *synonymous* iff there exists an ontology T_3 with the signature $\Sigma(T_1) \cup \Sigma(T_2)$ that is a definitional extension of T_1 and T_2.

If there is an interpretation of T_A in T_B, then there exists a set of sentences (referred to as *translation definitions*) in the language $L_A \cup L_B$ of the following form, where $p_i(\overline{x})$ is a relation symbol in L_A and $\varphi(\overline{x})$ is a formula in L_B:

$$(\forall \overline{x})\, p_i(\overline{x}) \equiv \varphi(\overline{x})$$

Thus, T_B interprets T_A if there exists a set Δ of translation definitions such that

$$T_B \cup \Delta \models T_A$$

T_B faithfully interprets T_A if $T_B \cup \Delta$ is a conservative extension of T_A.

2.2 Existing Merging Techniques

Within the applied ontology community, there exist various terms used to describe the notion of *ontology merging*; some of these terms have slight differences in the notion of merging but all agree that a *new* ontology is created from two ontologies. In (Choi et al., 2006), the authors indicate that ontology merging is the process of generating a new ontology from two or more existing and different ontologies that contain similar notions of a given subject. In (Euzenat and Shvaiko, 2007), the notion is similar, where the new merged ontology contains the knowledge of the source ontologies. Other notions of merging discussed in (de Bruijn et al., 2006; Zimmermann et al., 2006) indicate that ontology merging results in a new ontology that is a union of two source ontologies, and captures all of the knowledge found in the source ontologies.

Bridge axioms are another term used to describe axioms that relate the terms of two or more ontologies together, and serve as the basis for ontology merging when the ontologies are expressed in the same language (Euzenat and Shvaiko, 2007; Zimmermann et al., 2006). They are often written in the form of subsumption axioms (Zimmermann et al., 2006; Stuckenschmidt et al., 2005); we make the distinction here that the notion of 'bridging' used in our approach is not restricted to subsumption axioms, but of the creation of an ontology (resulted from the merge) and the usage of translation definitions to illustrate faithful interpretations between theories.

Ontology mappings are used to formalize the correspondences between the entities of one ontology with the entities of another (Euzenat and Shvaiko, 2007). There are several notions of mappings which will not be discussed in this section; we direct the reader to (Choi et al., 2006) for such distinctions. In this work, we utilize *translation definitions* to specify the mappings between the theories.

Our approach to ontology merging is distinct from these existing techniques as it utilizes ontology verification in the process to ensure that the source theories, along with the new intermediary theory, are faithfully interpretable with one another. As well, we provide direct mappings between the concepts in the ontologies through the use of translation definitions which are first-order axiomatizations of the interpretations between the ontologies.

3 BACKGROUND

DOLCE is often known as an ontology of endurants (objects) and perdurants (processes). Similarly, the PSL ontology also axiomatizes classes and properties of objects and activity occurrences. In this section, we briefly review these two upper ontologies, and we review the different ontological commitments that they make. It will be these differences which will become the focus for the design of new bridge ontologies in the remainder of the paper.

3.1 PSL-Core

The Process Specification Language (PSL) is an ontology designed to facilitate the correct and complete exchange of process information among manufacturing systems (Grüninger, 2009). These applications include scheduling, process modelling, process planning, production planning, simulation, and project management. The PSL ontology is organized into a core theory, PSL-Core[2] and a set of partially ordered extensions; the core ontology consists of four disjoint classes: *activities* can have zero or more occurrences, *activity occurrences* begin and end at time points, *time points* constitute a linear ordered set with end points at infinity, and *objects* are elements that are not activities, occurrences, or time points (Grüninger, 2009). In PSL, the ternary relation, $participates\_in(x,o,t)$, is used to specify that an object x participates in an activity occurrence o at a time point t. In other words, an object can participate in an activity occurrence only at those time points at which both the object exists and the associated activity is occurring.

There are five additional modules within the PSL ontology – $T_{occtree}$ (which is closely related to situation calculus), $T_{subactivity}$ (which axiomatizes the composition relation on activities), T_{atomic} (which axiomatizes concurrent activities), $T_{complex}$ (which axiomatizes complex activities), and T_{actocc} (which axiomatizes the composition relation on occurrences of complex activities). However, none of these notions correspond to concepts within DOLCE, so the only part of the PSL ontology considered in this paper is restricted to PSL-Core.

3.2 DOLCE

As the first module of the WonderWeb library of foundational ontologies, the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) aims to capture the categories which underlie natural language and human common sense (Masolo et al., 2003). DOLCE is based on the distinction between enduring and perduring entities, referred to as continuants and occurrents, where the fundamental difference between the two is related to their behaviour in time (Masolo et al., 2003). *Endurants* are wholly present at any time: they are observed and perceived as a complete concept, regardless of a given snapshot of time. *Perdurants*, on the other hand, extend in time

[2]http://colore.oor.net/psl_core/psl_core.clif

by accumulating different temporal parts, so they are only partially present at any given point in time.

Based on the distinction between endurants and perdurants, DOLCE has been partially modularized into the following modules in (Chui, 2013): $T_{dolce\_taxonomy}$ (which axiomatizes the subsumption and disjointness of DOLCE categories), $T_{dolce\_mereology}$ (which axiomatizes parthood for atemporal entities), $T_{dolce\_time\_mereology}$ (which axiomatizes a mereology on time intervals), $T_{dolce\_present}$ (which axiomatizes an entity's existence in time), $T_{dolce\_temporary\_parthood}$ (which axiomatizes the time-indexed parthood of entities), $T_{dolce\_constitution}$ (which axiomatizes the co-location of different entities in the same space-time), and $T_{dolce\_participation}$ (which axiomatizes the participation of entities).

The authors of (Kutz and Mossakowski, 2011) have shown that the first-order axiomatization of DOLCE is consistent and have provided an alternative modularization of ontology; we have adapted their axioms in the results of this paper and included them in COLORE[3]. The concepts found within the $T_{dolce\_participation}$, $T_{dolce\_time\_mereology}$, and $T_{dolce\_present}$ theories are considered in this work as they correspond with concepts found in PSL-Core and other time ontologies in COLORE.

3.3 Relationships among the Ontologies

In order to understand how the PSL ontology is related to DOLCE, we begin by outlining some observations of both ontologies. As shown on the left-hand side of Figure 1, the various subtheories of DOLCE are depicted as modules in the ontology. There are no relations in the PSL ontology that intuitively correspond to the concepts of temporary parthood, constitution, or dependence within DOLCE. On the other hand, the PSL ontology focuses on relations between activity occurrences, objects, and time points. In this paper, we therefore focus on the three subtheories of DOLCE that axiomatize relationships between perdurants, endurants, and time intervals: participation $T_{dolce\_participation}$, being present $T_{dolce\_present}$, and time mereology $T_{dolce\_time\_mereology}$. In DOLCE, *time intervals* are used to describe temporal objects in $T_{dolce\_participation}$ and $T_{dolce\_present}$, all of which contain $T_{dolce\_time\_mereology}$. DOLCE does not contain an ordering on time, but has a time mereology. In contrast, the T_{psl_core} PSL-Core ontology uses *time points* to describe the temporal aspects of objects and activity occurrences, as well as uses an ordering on time, but does not contain a time mereology. From this observation, both ontologies appear to have intuitions of perdurants/endurants and activity occurrences/objects being present and participating in some time construct, yet these intuitions seem to be quite different, and the relationship between the two ontologies is not obvious.

[3]http://colore.oor.net/dolce/

The second DOLCE module that we consider is $T_{dolce\_participation}$; this subtheory contains the following axiom (`Ad35` in (Masolo et al., 2003)) which indicates every endurant participates in some perdurant at a given time object:

$$\forall x\, ED(x) \supset \exists(y,t)\, PC(y,x,t) \quad (1)$$

A similar axiom is found in T_{psl_core} that indicates activity occurrences require an object to participate in them. From these observations, we can hypothesize that perdurants and endurants from DOLCE are equivalent to activity occurrences and objects in PSL, respectively. We can further conjecture that the notion of participation $PC(x,y,z)$ in DOLCE is equivalent to the $participates\_in(x,y,t)$ relation in PSL: for any object x, activity occurrence y, and time interval z, there exists a time construct t that is equivalent to the time interval z, where x participates in y during t. We write these equivalences as the following *translation definitions*:

$$\forall x\, PD(x) \equiv activity\_occurrence(x) \quad (2)$$

$$\forall x\, ED(x) \equiv object(x) \quad (3)$$

$$\forall x\, T(x) \equiv timeinterval(x) \quad (4)$$

$$\begin{aligned} &\forall x \forall y \forall z\, (PC(x,y,z) \equiv object(x) \wedge \\ &activity\_occurrence(y) \wedge timeinterval(z) \wedge \\ &(\forall t beforeEq(beginof(z),t) \wedge beforeEq(t,endof(z)) \supset \\ &participates\_in(x,y,t))). \quad (5) \end{aligned}$$

The DOLCE ontology also contains a taxonomy of classes of perdurants and endurants. The PSL ontology does not contain a corresponding taxonomy of activities, activity occurrences, or objects. Nevertheless, DOLCE does not provide additional axioms that distinguish among the different classes of perdurants, apart from the taxonomic axioms. We therefore do not pursue a mapping from this part of the DOLCE ontology to the PSL ontology.

We can extract the following obstacles from our observations:

1. PSL-Core utilizes a time point ontology, which has an ordering but not a mereology.
2. DOLCE utilizes a time interval ontology, which has a mereology but no ordering.
3. Both PSL-Core and DOLCE make different ontological commitments on how objects/endurants participate in activity occurrences/perdurants.

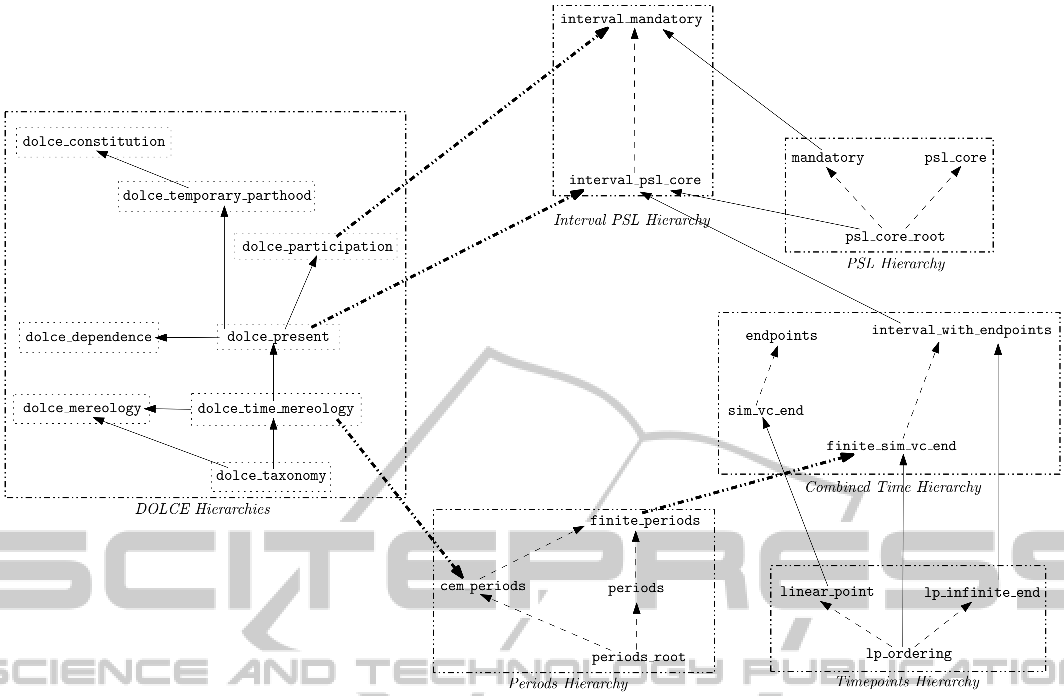

Figure 1: Relationships between DOLCE modules and theories in COLORE. Solid lines indicate *conservative extensions*, dashed lines indicate *non-conservative extensions*, and the bolded dash-dot-dotted lines indicate *faithful interpretations* between ontologies.

In the sections that follow, we address how to overcome these obstacles by creating new ontologies to integrate the ontologies describing time points and orderings with ontologies describing time intervals and mereologies. In order to identify the specific relationship between the two ontologies of DOLCE and PSL, it should be possible to add a *mereology* of time intervals to PSL, or add an ordering to DOLCE, and then determine whether the resulting extensions of DOLCE and PSL *faithfully interpret* each other. COLORE contains numerous mathematical theories that can assist us in this regard – the Combined Time hierarchy $\mathbb{H}^{combined\_time}$ contains time ontologies that utilize both time point and time interval constructs, and are able to interpret a mereology on time points and time intervals. Figure 1 illustrates the bridges that can be created to formalize the relationships between the ontologies.

It may be noted that there are two different intuitions about bridging ontologies that are being explored here. We first consider new ontologies which are created as either nonconservative extensions of ontologies in existing hierarchies, or as merged ontologies, that is, they are conservative extensions of a set of other ontologies from different hierarchies. We will see this in the role played by the ontologies in the Combined Time and Interval PSL hierarchies. An alternative intuition is that a bridging ontology is strong enough to faithfully interpret one ontology while conservatively extending another, thus providing a way of embedding the two ontologies within the bridging ontologies. We will see this in the role played by ontologies in the Interval PSL hierarchy.

It is also interesting to see how this approach to bridging ontologies is related to the notion of bridge axioms. For bridging ontologies which are the merge of other ontologies, there exist sentences whose signature is the union of the signatures of the merged ontologies. For example, we will see that there exist axioms in the ontologies of the Combined Time hierarchy which use relations on both time points and time intervals. Such axioms correspond to the bridge axioms in (Stuckenschmidt et al., 2005; Euzenat and Shvaiko, 2007). On the other hand, for bridging ontologies which faithfully interpret an ontology, we do not find such sentences. Instead, the translation definitions that specify the interpretation play the role of bridge axioms between the two ontologies.

4 MERGING TIME POINT AND INTERVAL ONTOLOGIES

To address the first obstacle, we utilize existing combined time ontologies to integrate time points and time intervals, and mereologies and orderings. In this way, existing temporal ontologies found in COLORE can be used to analyze the interpretations between the DOLCE and PSL. Here we briefly outline the time point and time interval ontologies used. We then examine a set of time ontologies from COLORE which merge the time point ontologies with the time interval ontologies.

4.1 The Time Points Hierarchy

Within this hierarchy are ontologies that describe time in terms of time points and that introduce a partial ordering on the set of time points using the binary relation $before(x,y)$. We are particularly interested in two of these ontologies, based on the roles they play as modules of other ontologies. The linear point theory, T_{linear_point}[4], derived from axioms found in (Hayes, 1996), is a simple ontology whose axioms state that time points infinitely extend a timeline in both forward and backward directions. The linear time points with endpoints at infinity theory, $T_{lp\_infinite\_end}$[5], derived from axioms found in (Hayes, 1996), also represents a linear ordering on time points that infinitely extends in both forward and backward directions, but it contains axioms that enforce the existence of endpoints at infinity in both directions.

4.2 The Periods Hierarchy

The axioms for the periods hierarchy, $\mathbb{H}^{periods}$, were proposed in (van Benthem, 1991), and additional information about other ontologies in this hierarchy can be found in (Grüninger et al., 2012). We are interested in the in the weakest theory of this hierarchy, $T_{periods}$, since it is used by $T_{endpoints}$, which is described in Section 4.3. The Minimal Theory of Periods, $T_{periods}$, constitutes the minimal set of conditions that must be met by any period structure (van Benthem, 1991). It contains two relations, $precedence(x,y)$ and $inclusion(x,y)$, and two conservative definitions, $glb(x,y,z)$ and $overlaps(x,y)$, as its non-logical lexicon. Every element in the domain is considered a time interval, and there are transitivity and irreflexivity axioms for the $precedence(x,y)$ relation, making it a strict partial order; similarly, the transitivity, reflexivity, and anti-symmetry axioms for the $inclusion(x,y)$ relation make it a partial order. As well, the axiom, $glb(x,y,z)$, guarantees the existence of greatest lower bounds between overlapping intervals defined by $overlaps(x,y)$.

[4]http://colore.oor.net/timepoints/linear_point.clif

[5]http://colore.oor.net/timepoints/lp_infinite_end.clif

An interesting property in these ontologies is the convexity of time intervals. Intuitively, convex intervals are those which have no gaps (Ladkin, 1986)[6]. The convexity of time intervals requires an ordering over time intervals and a mereology, and hence it can be defined by ontologies in the $\mathbb{H}^{periods}$ hierarchy. However, convexity is not definable in DOLCE since it lacks an ordering on time intervals.

4.3 The Combined Time Hierarchy

Given that we want to merge ontologies from the time points hierarchy with ontologies from the periods hierarchy, we need to consider ontologies that include both time points and time intervals as primitives, and define a set of functions and relations specifying the interactions between them. These time ontologies[7] are derived from the theories presented in (Hayes, 1996), and have been modified and verified in (Gruninger and Ong, 2011). Depending on the relations and functions used, these theories can represent time in very different ways. For example, the theory of endpoints, $T_{endpoints}$, defines time points only as the boundary of time intervals, where every interval is associated with exactly two time points: the begin of and end of the interval. In contrast, the theory of time point continuum, $T_{point\_continuum}$, defines intervals by the set of adjacent time points in which they are contained; another theory, $T_{vector\_continuum}$ introduces the concept of directionality by allowing 'backward intervals' where the end of point is before the begin of point in the timeline.

The theory of endpoints, $T_{endpoints}$[8], combines the language of intervals and points by defining the *beginof*, *endof*, and *between* functions to relate time intervals to time points and vice-versa. In this hierarchy, this theory imports axioms from T_{linear_point} that define a binary $before(x,y)$ relation between time points as transitive and irreflexive, and asserts that all time points are linearly ordered and infinite in both directions. As well, this theory includes axioms that define the $meets\_at(i,x,j)$ relation as one between two intervals and the point at which they meet along, restrict $beginof(i)$ to always come before the $endof(i)$ function, and states that intervals are between two points if they are properly ordered.

The vector continuum theory, $T_{vector\_continuum}$[9], in-

[6]Additional information about the various relations found in convex and non-convex intervals can be found in (Ladkin, 1986).

[7]http://colore.oor.net/combined_time/

[8]http://colore.oor.net/combined_time/endpoints.clif

[9]http://colore.oor.net/combined_time/vector_continuum.clif

troduces the notion of orientation of intervals, and also imports T_{linear_point}. It contains the same three functions ($beginof(i)$, $endof(i)$, and $between(x,y)$) that transform time intervals into time points and vice-versa, but differs in its definition of $between(x,y)$ by allowing the formation of intervals whose *endof* point is equal to or before its *beginof*. Thus, every interval in $T_{vector\_continuum}$ has a 'reflection' in the opposite direction via the $back(i)$ function; intervals oriented in the forward direction are defined normally where $beginof(i)$ is before $endof(i)$. As well, single-point intervals, known as *moments*, are defined as intervals whose $beginof(i)$ and $endof(i)$ points are the same.

4.4 Composing the Theory of Intervals with Endpoints

The combined time hierarchy contains ontologies whose models combine structures for time points and time intervals. These ontologies were first proposed in (Hayes, 1996), and assume an import of the $T_{endpoints}$ theory, where every time interval is associated with two time points. However, T_{psl_core} contains a *time point* ontology that axiomatizes a linear ordering with endpoints at infinity, whereas $T_{endpoints}$ axiomatizes a time point ontology in which the linear ordering does not have such maximum and minimum time points. Consequently, we need to create a new theory, $T_{interval\_with\_endpoints}$, in $\mathbb{H}^{combined\_time}$ that contains the time interval axioms of $T_{endpoints}$ with a different time point ontology. It is this new time ontology which will be used to extend T_{psl_core} to make it compatible with the existence of time intervals.

The new intervals with endpoints theory, $T_{interval\_with\_endpoints}$, imports axioms from $T_{finite\_sim\_vc\_end}$ from $\mathbb{H}^{combined\_time}$ and $T_{lp\_infinite\_end}$ from $\mathbb{H}^{timepoints}$. The primary difference between the $T_{finite\_sim\_vc\_end}$ and $T_{sim\_vc\_end}$ ontologies within $\mathbb{H}^{combined\_time}$ is that different time point ontologies are used in each theory; while both ontologies share a common set of axioms ($T_{lp\_ordering}$) additional axioms in T_{linear_point} make $T_{sim\_vc\_end}$ different from $T_{finite\_sim\_vc\_end}$, as depicted in Figure 1. Consequently, $T_{interval\_with\_endpoints}$ non-conservatively extends $T_{finite\_sim\_vc\_end}$ since it contains the same time interval axioms as $T_{finite\_sim\_vc\_end}$, but different time point axioms from $T_{lp\_infinite\_end}$. The axioms of $T_{interval\_with\_endpoints}$ can be found in COLORE[10].

Recall that the DOLCE ontology has a mereology on time intervals, but that there is no ordering relation on time intervals; on the other hand, the combined time ontologies have an ordering over time intervals by which an mereology can be defined. In this way, the periods hierarchy *bridges* DOLCE and combined time hierarchies together since $T_{periods}$ is the common theory between them. We note that the dash-dot-dotted arrows in Figure 1 outline the faithful interpretations between $\mathbb{H}^{dolce}$ and $\mathbb{H}^{periods}$, and $\mathbb{H}^{periods}$ and $\mathbb{H}^{combined\_time}$; however, these are faithful interpretations are conjectured and proofs will be addressed in future work. In this paper, we only discuss the composition of theories needed to prove the faithful interpretations between DOLCE and PSL.

[10]http://colore.oor.net/combined_time/interval_with_endpoints.clif

5 EXTENDING T_{PSL_CORE}

To address the second obstacle, we extend the PSL-Core theory with time intervals and interpret DOLCE in this new ontology. Within PSL, *activity occurrences* are considered to be occurrents, while *objects* are represented by continuants (Grüninger, 2009). The relation $participates\_in(x,o,t)$ is used to specify that an object x participates in activity occurrence o at time point t. Since DOLCE does not utilize time points but time intervals in its time mereology, an extension of T_{psl_core}[11] must be created in order to map the $participates\_in(x,o,t)$ relation to a relation on time intervals.

5.1 Theory of PSL-Core Root

A subset of the axioms in T_{psl_core} were extracted to create the $T_{psl\_core\_root}$ theory. The following *closure* axiom from T_{psl_core} was removed

$$\forall x\,(activity(x) \lor activity\_occurrence(x) \lor timepoint(x) \lor object(x)) \tag{6}$$

We need a theory which can incorporate both time points and time intervals, and it is easy to see how such a closure axiom is problematic, since it precludes the existence of time intervals as a distinct class. In other words, there can be no extension of T_{psl_core} that contains an axiomatization of time intervals. It is easy to see that T_{psl_core} is a non-conservative extension of $T_{psl\_core\_root}$. All new theories that incorporate time intervals into the PSL ontology are conservative extensions of $T_{psl\_core\_root}$.

5.2 Theory of Mandatory Participation

The original T_{psl_core} contains a weak axiomatization of the $participates\_in(x,o,t)$ relation, and does not

[11]We could not modify the axioms found in T_{psl_core} since the axioms are standardized in ISO 18629-11:2005.

$$\forall x\,(object(x) \supset (\exists o \exists t\; participates\_in(x,o,t))) \quad (7)$$

$$\forall o \forall t\,(activity\_occurrence(o) \wedge is\_occurring\_at(o,t) \supset (\exists x\; participates\_in(x,o,t))) \quad (8)$$

Figure 2: Axioms found in $T_{mandatory}$.

impose any conditions beyond requiring that an activity is occurring at the same time that the object exists. There are no requirements that an object must participate in some activity occurrence, or that an activity occurrence always have some object participating in it. We can therefore define a new *non-conservative* extension of $T_{psl\_core\_root}$ called $T_{mandatory}$ to take into account the *mandatory* participation of PSL objects in a temporal construct. The axioms found in this extension import $T_{psl\_core\_root}$ and *do not* include the $between(x,y,z)$ and $before(x,y,z)$ relations found in T_{psl_core} since they involve the usage of time points, not time intervals, to describe the participation of objects in activity occurrences and time objects. Figure 2 lists all of the axioms found in $T_{mandatory}$, and the axioms can be found in COLORE[12]. Axiom 7 indicates that every object x has to participate in some activity occurrence o at a time object t, and Axiom 8 indicates that, for every activity occurrence o that occurs during the time object t, there exists an object that also participates in that time object.

In $T_{mandatory}$, we *do not* commit to a specific type of temporal object for object participation, but we note that there needs to be a 'bridge' of sorts to connect the DOLCE and PSL ontologies together. Consequently, we are interested in creating a new *bridge ontology* that contains the PSL constructs that are used with time intervals. We discuss this new $\mathbb{H}^{interval\_psl}$ hierarchy in the next section.

5.3 The Interval PSL Hierarchy

Since the PSL ontology only describes object and activity occurrences with respect to time points, we need to create a time interval version of the PSL ontology. This leads to a new hierarchy, called $\mathbb{H}^{interval\_psl}$, with $T_{interval\_psl\_core}$ as its root theory. This hierarchy contains the time interval versions of the T_{psl_core} and $T_{mandatory}$ ontologies which are named $T_{interval\_psl\_core}$ and $T_{interval\_mandatory}$, respectively, and are depicted in Figure 1. Each of these ontologies is briefly described below, and can be found in COLORE[13].

[12]http://colore.oor.net/psl_core/mandatory.clif

[13]http://colore.oor.net/interval_psl/

$$\forall x\,(timeinterval(x) \supset \neg(activity(x) \vee activity\_occurrence(x) \vee timepoint(x) \vee object(x))) \quad (9)$$

$$\forall x \forall y\,(psl\_interval(x,y) \equiv (object(x) \vee activity\_occurrence(x)) \wedge timeinterval(y) \wedge beginof(x) = beginof(y) \wedge endof(x) = endof(y)) \quad (10)$$

$$\forall x \forall y \forall z\,(overlay(x,y,z) \equiv (\exists i_1 \exists i_2\,(psl\_interval(x,i_1) \wedge psl\_interval(y,i_2) \wedge beginof(i_2) = beginof(z) \wedge endof(i_1) = endof(z)))) \quad (11)$$

Figure 3: Axioms of $T_{interval\_psl\_core}$.

The ontologies in this hierarchy import axioms from $T_{psl\_core\_root}$ and $T_{interval\_with\_endpoints}$. In order to ensure that the time interval version of $T_{psl\_core\_root}$ contains axioms that describe time intervals, and not time points, $T_{interval\_with\_endpoints}$ is used to describe the time objects found in this compiled ontology.

Three axioms are added to $T_{interval\_psl\_core}$ in addition to the imported ontologies and are outlined in Figure 3. Axiom 9 indicates that a time interval is not an activity, activity occurrence, object, or time point. In Axiom 10, the relation, $psl\_interval(x,y)$, is introduced to relate a time interval with the begin of and end of an activity occurrence or object. Finally, the $overlay(x,y,z)$ relation is introduced in Axiom 11 to describe a time interval z that overlays[14] activity occurrences x and y. However, it may not necessarily be the case that both activity occurrence/object y overlays an activity occurrence/object x, or vice versa. This axiom is included in case such overlaying of intervals does occur.

5.4 Theory of Mandatory Intervals

Finally, we have the theory of mandatory intervals which imports axioms from $T_{interval\_psl\_core}$ and $T_{mandatory}$. Since we would like to show that $T_{dolce\_participation}$ can faithfully interpret the time interval versions of PSL ontologies from $T_{interval\_psl\_core}$, we extended $T_{interval\_psl\_core}$ to include the time inter-

[14]The terms *overlap* and *intersect* were not used to describe this relation since they are used in mereology ontologies. To be consistent with PSL, we decided to use the term *overlay* to describe the relationship where time intervals may overlay one another.

val versions of the axioms from $T_{mandatory}$. No additional axioms are included in this ontology and it can be found in COLORE[15]. Essentially this ontology assigns time intervals[16] to $T_{interval\_psl\_core}$ to indicate the *mandatory* participation of PSL over a time interval. The right side of Figure 1 summarizes the relationships between the Interval PSL, PSL, and Combined Time hierarchies.

6 INTERPRETATIONS BETWEEN DOLCE AND PSL

In order to determine whether PSL can faithfully interpret the subtheories of DOLCE, we first need to modify $T_{dolce\_present}$. This module of DOLCE contains class $Q(x)$ of qualities, which is problematic – $T_{psl\_core\_root}$ is unable to define what a quality is because it is unable to discern which $object(x)$ is an endurant $ED(x)$ or a quality $Q(x)$. We must therefore specify a subtheory of $T_{dolce\_present}$ that does not include qualities for this portion of the interpretation. The axioms of this subtheory $T^*_{dolce\_present}$ can be found in COLORE[17].

The DOLCE subtheories of $T_{dolce\_participation}$ and $T_{dolce\_time\_mereology}$ are able to interpret the $T_{interval\_mandatory}$ and $T_{interval\_psl\_core}$ ontologies in $\mathbb{H}^{interval\_psl}$, respectively. This is graphically depicted in Figure 1, where the dashed arrows depict the interpretations from the DOLCE ontology to the Interval PSL ontology.

6.1 Interpretations between $T_{interval\_psl\_core}$ and $T^*_{dolce\_present}$

From our brief discussion of the theories found in COLORE, we make the observation that the concept of *parthood* in DOLCE is equivalent to the *inclusion* of time intervals in $T_{interval\_psl\_core}$:

$$\forall t_1 \forall t_2\, (P(t_1,t_2) \equiv timeinterval(t_1) \wedge timeinterval(t_2) \wedge beforeEq(beginof(t_2), beginof(t_1)) \wedge beforeEq(endof(t_1), endof(t_2))) \quad (12)$$

Thus, we can say that the time interval t_1 is *part of* time interval t_2: the beginning of t_2 can either be before or equal to the beginning of t_1, and the end of t_1 can either be before or equal to the end of t_2.

Furthermore, we can state that the concept of being present in DOLCE is equivalent to the concept of an object or activity occurrence that exists in a given time interval, where the beginning of the time interval is the time point in which an object or activity occurrence starts, and that the end of the time interval is the time point in which the object or activity occurrence ends.

$$(\forall x \forall y \forall t\, (PRE(x,t) \equiv (object(x) \vee activity\_occurrence(x)) \wedge timeinterval(t) \wedge beforeEq(beginof(x), beginof(t)) \wedge beforeEq(endof(t), endof(x)))). \quad (13)$$

We note that, in $psl\_interval(x,y)$, a unique time interval is associated with an object or activity occurrence in PSL. Similarly, the time interval associated in $PRE(x,t)$ in DOLCE need not be a time interval at which an endurant or perdurant is present. The translation definition for the *sum* of time intervals is based on the definition of the overlaps relation in DOLCE:

$$\forall x \forall y\, overlaps(x,y) \equiv (before(beginof(x), beginof(y)) \wedge before(endof(x), endof(y))) \vee (before(beginof(y), beginof(x)) \wedge before(endof(y), endof(x))). \quad (14)$$

$$\forall x \forall y \forall z\, SUM(z,x,y) \equiv timeinterval(x) \wedge timeinterval(y) \wedge timeinterval(z) \wedge (\forall w\, (overlaps(w,z) \equiv (overlaps(w,x) \vee overlaps(w,y)))). \quad (15)$$

To show that $T_{interval\_psl\_core}$ interprets $T^*_{dolce\_present}$, we define endurants and qualities in DOLCE to be equivalent to objects in PSL, perdurants to equivalent to activity occurrences, and time intervals in DOLCE to be equivalent to time intervals in Interval PSL. In regards to mereology, a time intervals t_1 is defined to be a part of a time interval t_2 if the begin of t_2 is before or equal to t_1 and the end of t_1 is before or equal to t_2. The $PRE(x,t)$ relation in DOLCE is defined to be equivalent to an object or activity occurrence that occurs during a time interval. Finally, the $SUM(z,x,y)$ relation in DOLCE is defined to be a time interval z is the sum of the time intervals of two activities x and y in Interval PSL.

Theorem 1. *$T_{interval\_psl\_core}$ faithfully interprets $T^*_{dolce\_present}$.*

Proof. Let Δ_1 be the set of translation definitions

[15] http://colore.oor.net/interval_psl/interval_mandatory.clif

[16] Recall that we did not commit to a particular temporal construct in $T_{mandatory}$.

[17] http://colore.oor.net/dolce_present/dolce_present_star.clif

found in COLORE[18]. Using Prover9, we show[19] that

$$T_{interval\_psl\_core} \cup \Delta_1 \models T^*_{dolce\_present}$$

□

It should be noted that, if we consider their entire sets axioms, DOLCE and PSL are not comparable with respect to definable interpretations. Nevertheless, we can identify subtheories of each ontology for which we can specify interpretability. For PSL, we needed to weaken the closure axiom and, for DOLCE, we needed to consider the subtheory which omits qualities from the domain.

6.2 Interpretations Between $T_{interval\_mandatory}$ and $T_{dolce\_participation}$

For the interpretation of $T_{interval\_mandatory}$ and $T_{dolce\_participation}$, we reuse the set of translation definitions Δ_1 from the previous section (because $T_{interval\_mandatory}$ imports $T_{interval\_psl\_core}$), along with the additional translation definition described below.

Since the DOLCE ontology contains axioms for participation, we make the observation that the participation relation, $PC(x,y,z)$, is similar to the $participates\_in(x,y,t)$ relation found in PSL. Thus, we can state that any x and y that participate in z in DOLCE is equivalent an object x that participates in an activity occurrence y in a given time interval z and, at *every* time point in that interval, x *participates* in y.

$$\forall x \forall y \forall z \forall t\ (PC(x,y,z) \equiv object(x) \wedge activity\_occurrence(y) \wedge timeinterval(z) \wedge (beforeEq(beginof(z),t) \wedge beforeEq(t,endof(z)) \supset participates\_in(x,y,t))) \quad (16)$$

Theorem 2. *$T_{interval\_mandatory}$ faithfully interprets $T_{dolce\_participation}$.*

Proof. Let Δ_2 be the set of translation definitions found in COLORE[20]. Using Prover9, we show[21] that

$$T_{interval\_mandatory} \cup \Delta_1 \cup \Delta_2 \models T_{dolce\_participation}$$

□

[18]http://colore.oor.net/interval_psl/mappings/interval_psl_core2dolce_present.clif

[19]Proofs can be found at http://colore.oor.net/dolce_present/interprets/output/.

[20]http://colore.oor.net/interval_psl/mappings/interval_mandatory2dolce_participation.clif

[21]Proofs can be found at http://colore.oor.net/dolce_participation/interprets/output/.

7 SUMMARY

In cases where direct mappings cannot be specified between ontologies, one can design new ontologies that can serve as bridges between the ontologies, and which then allow mappings to be specified. In this paper we have explored how this can be done with the DOLCE and PSL ontologies. In particular, faithful interpretations specified between the DOLCE ontology and ontologies within the Common Logic Ontology Repository (COLORE) have shown that multiple 'bridges' were needed before any analyses with the $T_{dolce\_participation}$ and $T_{dolce\_present}$ theories could be carried out with theories in COLORE. Firstly, we saw that the Combined Time hierarchy *bridges* the Time Points and Periods hierarchies together to allow us to merge ontologies of time points and time intervals. Secondly, the Interval PSL hierarchy *bridges* both the PSL and DOLCE ontologies together to allow us to do the mapping between them and to identify the faithful interpretations of mereology and orderings in both time points and time intervals. This exercise in bridging ontologies together demonstrates how we can axiomatize the relationships between theories and compose new theories that are required for the bridging task.

The methodology presented in this paper is based on techniques for ontology verification that use an ontology repository to specify faithful interpretations among ontologies. It should therefore be applicable to any set of ontologies which have been verified. Nevertheless, ontologies which have not been explicitly modularized still pose a challenge, and the interplay between ontology merging and decomposition merit further exploration.

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