

Expressing time-dependent relations through temporal qualifications

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Abstract. We discuss the difficulties of representing different forms of temporal relatedness in OWL 2, given its limitation to binary relationships. Based on the fact that temporary relatedness is important for modelling domains that are characterised by dynamic phenomena, we propose a reification scheme to express temporary and permanent relatedness that combines semantic accuracy, ease of use and ontological rigour. Central to this scheme is the notion of temporal qualification that provides a means to abstract from parts of the history of a continuant.

Keywords. Relation, time, stage, phase, top-level ontology, BFO, reification, ternary relation, OWL 2

1. Introduction

One of the most salient features that can be used to make distinctions between different kinds of entities in top-level ontologies is their relationship to time. It gives rise to the widely accepted distinction between continuants and occurrents, which is present in top-level ontologies such as BFO [1], DOLCE [2] and GFO [3], although not all of them use the same terminology to express this distinction. In the conventional picture, continuants are characterised as entities that persist through time and are wholly present at every point of their existence, while occurrents – being temporally unfolding entities – are only completely present over an extended period of time.

But not only do entities need to be differentiated based on their temporal mode of existence, temporal aspects also have to be taken into account when specifying the

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relationships between those entities. One particular problem arises when the topic domain in question includes not only static, but also dynamic aspects of reality. This is the case for most of the life sciences, where the continuants not only persist, but also change over time. This is especially evident in that the shape and the constitution of biological organisms are in continuous flux. Consequently, any relational expression which makes reference to a particular continuant can have different truth values at different times and would therefore be ambiguous if time were not made explicit in the statement. For example, each of the following pairs of statements may be true together:

A ripening apple:

bearerOf(Apple_123, GreenColor_123, 2011-06-20)
bearerOf(Apple_123, RedColor_123, 2011-07-01)

Joe's body parts before and after an appendectomy:

partOf(Joe's_Appendix, Joe, 2011-08-25)
 not (**partOf**(Joe's_Appendix, Joe, 2011-08-26))

The soprano Mary participating in a performance of Beethoven's 9th symphony, during the 4th movement only:

not (**participatesIn**(Mary, Beethoven_9th_Symphony_Performance_1234, 2012-01-01:20:05))
participatesIn(Mary, Beethoven_9th_Symphony_Performance_1234, 2012-01-01:20:55)

As we see, a time index is necessary for any statement asserting a relation that changes through time, and this includes many statements involving an independent continuant, such as in the above examples involving apple_123, Joe or Mary..

Top-level ontologies thus need to take into account temporality in order to provide an accurate model for the interrelations of continuants. Unfortunately, if one strives to promote the use of top-level ontologies in application contexts because of their benefits for ontology re-use, data integration or overall accuracy, complying with this need can become quite complex. This is because ontological accuracy, alone, is often not the sole guiding principle in ontology design. Instead, at least two additional issues need to be taken into account:

1. The effort required on part of the ontology engineers: In many cases they are domain experts not trained in formal logic and may have difficulties if the modelling is not intuitive. We consider this a major reason why four-dimensionism is not the ontological approach of choice: Most of us do not normally think of Mary or apple #123 as four-dimensional space-time worms, but rather as three-dimensional things.
2. The representation formalisms available, together with the tools (editors, reasoners) that support them: These formalisms need to compromise between expressiveness and computational complexity. Currently, OWL 2 (*SROIQ*) is the most expressive formalism that is standardized, and for which there is wide availability of authoring tools and reasoners

All profiles of OWL 2 allow only binary relations between individuals, called object properties. But while there has been work on expressive description logics that try to transcend this limitation [4] and also on description logics that explicitly account for temporality (e.g. [5]), there is no strong push towards standardisation of those formalisms, and tools suitable for end users are not readily available. It has thus been acknowledged that there is a need for solutions that work within the confines of present technologies [6].

Throughout the paper, we will use “**rel**” as an example and general placeholder for any relation that developers might want to use in an ontology. If this relation is originally a ternary relation **rel** (a, b, t) with explicit time index, the ontology engineer faces the problem how to express it as a binary object property **rel**. For example, consider the following class expression (as expressed in Manchester Syntax [7]):

$A \text{ subClassOf } \mathbf{rel} \text{ some } B$

Different interpretations of this expression are possible, based on the “temporal strength” of the relational term “**rel**”, which can be rendered in FOL as follows (note that **inst** is the time-indexed instantiation relation that holds between an individual and a class at some time t):

- (I) *Temporary relatedness*. For each instance of A there is some instance of B to which A is related by **rel** at some time.

$$\forall a \exists t_2: \mathbf{inst}(a, A, t_2) \rightarrow \exists b, (\mathbf{inst}(b, B, t_2) \wedge \mathbf{rel}(a, b, t_2))$$

Example: All apples are green at some time.

- (II) *Permanent relatedness*. For each instance of A there is some instance of B at all times related by **rel**.

Example: All cells always contain some water molecule.

Among the cases of (II) we could distinguish between those cases where an instance of A is always related to the very same instance of B, and those cases where it is related to some but not necessarily the same instance of B.

$$\begin{aligned} &\forall a, t: \mathbf{inst}(a, A, t) \rightarrow \exists b: \mathbf{inst}(b, B, t) \wedge \mathbf{rel}(a, b, t) \text{ vs} \\ &\forall a, \exists b, \forall t: \mathbf{inst}(a, A, t) \rightarrow \mathbf{inst}(b, B, t) \wedge \mathbf{rel}(a, b, t) \end{aligned}$$

We can say that A and B are *permanently specifically related* in the first group of cases, and *permanently generically related* otherwise. We will however not further pursue this distinction in this paper.

Our working hypothesis will be that both interpretations, “*temporary relatedness*” (I) and “*permanent relatedness*” (II) are relevant in the context of application ontologies. In what follows, we will attempt to sketch solutions for expressing these interpretations in OWL 2. Our primary point of reference will be the BFO top-level ontology, but the proposal sketched here could potentially be implemented in other top-level ontologies that are sufficiently similar to BFO.

2. Connection to the SNAP/SPAN distinction

BFO has traditionally maintained a strong distinction between 3D and 4D accounts of reality [8]. According to BFO, a 3D description of reality exposes certain truths about spatial and spatio-temporal phenomena, e.g. between ordinary objects that persist through time and the processes in which these objects are involved, while a four-dimensionalist view coalesces both into a single spatiotemporal account where, for example, processes involving objects are understood as something like “space-time worms”. But despite making this distinction, BFO maintains that these are not two incompatible descriptions of reality but instead that the continant and the occurrent views represent complementary perspectives of reality. Consequently, the ontological account of BFO is partitioned into two kinds of constituent ontologies. On the one hand, there are a series of 3D ontologies, which can basically be thought of as “snapshots” of reality at a given point in time and are hence called SNAP ontologies. On the other hand, the overarching four-dimensional picture is provided by a so-called SPAN ontology, to which all entities from SNAP ontologies are related by way of trans-ontological relations.

This highlights a significant mismatch between the theoretical framework of BFO and the constraints of OWL 2: the BFO solution is to use time-indexed SNAP ontologies for which a certain relational assertion holds. A similar mechanism is not specified for OWL 2 ontologies (though one can distinguish versions of an ontology) nor can the BFO approach be adopted as an informal convention if the ontologies are supposed to support automated reasoning. This is because of the following issue: assume that there are two SNAP ontologies, O_0 and O_1 , each describing whether the relation **rel** holds between two objects a and b at different points in time. Now, if in O_0 “**rel** (a , b)” is true, and in O_1 , “**rel** (a , b)” is false, we derive a contradiction once we construct a SPAN ontology O_s that references both O_0 and O_1 , due to the fact that the object property corresponding to **rel** shares the same namespace in all three ontologies. Consequently, if one chooses to produce a single ontology in which both SNAP and SPAN ontologies co-exist, there is room for only a single snapshot in that ontology.

This problem could be mitigated by introducing explicitly namespaced object properties, but this is highly impractical because it results in an extreme proliferation of relations, one for each point in time. Additionally, it is not ontologically sound to interpret these object properties as relationship universals, because they make claims about universals which are only applicable at one single point in time, which would be a very strange thing to claim about an universal unless it holds by virtue of an interpretation like (I) or (II). We thus need to look for alternative solutions to this problem that still capture the intended meaning of the SNAP/SPAN distinction, but are manageable for ontology engineers using OWL 2 or other languages from the description logic family.

3. Conventional Modellers’ Strategy for Temporalised Relations in OWL 2

Even though explicit semantics for modelling temporal dynamics are not available in OWL 2, modellers very often implicitly treat object properties as committing to a “for all times” interpretation in order to avoid obvious problems with the entailed models. For instance, in an anatomy ontology like the FMA, the object property

hasPart is transitive, and used in axioms such as *Lung* subClassOf **hasPart** some *LobeOfLung*, and *LobeOfLung* subClassOf **hasPart** some *BronchiopulmonarySegment*.

If the underlying interpretation were “for some time”, transitivity of the binary **hasPart** could no longer be taken for granted, as two **hasPart** assertions to be chained could belong to two different SNAP ontologies.

There is thus good reason to subscribe to interpretation (II), as this is the only available interpretation that has a possibility of being consistent with the semantics. But ontology builders are usually not aware of the fact that they have implicitly substituted the interpretation function (which maps syntactic constructs of OWL 2 to intended models) with a temporalised variant, regardless of whether they would have intended the permanent or temporary parthood variant if they had been aware thereof. Obviously, the interpretation must be equivalent to the OWL 2 direct semantics [9] in as far as it preserves syntactical structure and inferences and does not lead to additional expressivity. But it has – to our knowledge – never been made explicit what this substitution might consist of.

To address this mismatch and try to understand it better we sketch here an example of how the interpretation function might be modified. The general strategy of this interpretation is to augment the interpretations of class members and object properties in the OWL model with an additional time index t which specifies that the entity in question exists (object property holds) at t . Class instances then become pairs and object property instances triples. In order to keep the surface grammar and overall semantics intact, the interpretations of all OWL axioms will be prepended with a conditionalised universal quantification over t that specifies that the axiom should hold at all times that the entity in question exists. Time instants are hereby external to the domain. For example, the interpretation of a class assertion axiom that asserts that a is an instance of class C , as long as a exists, would then read (domain Δ , interpretation I):

$$\forall t (a^I, t) \in \Delta^I \rightarrow (a^I, t) \in C^I$$

We can thus only express rigid instantiation: Whenever an individual exists at all, it is also a member of the class it instantiates. The interpretation of temporality-sensitive relations will become clear when we spell out the semantic rules of existential quantification and value restriction, which both assert permanent relatedness because they apply existential quantification over the object property range so that at each point in time a different individual of class B can serve as a relatum. We will use the canonical structural syntax [10] to ease comparison with the specified semantics [9].

Existential quantification (**A rel some B**):

$$\text{ObjectSomeValuesFrom}(\mathbf{rel}, B)^I =_{\text{def}} \{(a, t) \in \Delta^I \mid \exists b: (a, b, t) \in \mathbf{rel}^I \wedge (b, t) \in B^I\}$$

Value restriction (**A rel only B**):

$$\text{ObjectAllValuesFrom}(\mathbf{rel}, B)^I =_{\text{def}} \{(a, t) \in \Delta^I \mid \forall b: (a, b, t) \in \mathbf{rel}^I \rightarrow (b, t) \in B^I\}$$

In object property assertions the time index is bound through universal quantification again:

$$\text{ObjectPropertyAssertion}(\mathbf{rel}, a, b)^I =_{\text{def}} \forall t (a^I, t) \in \Delta^I \rightarrow (a^I, b^I, t) \in \mathbf{rel}^I$$

Interpreting OWL 2 this way does justice to the semantics of class level relations intended by the relations ontology (RO) [11] and allows us to think of the following syntactical forms as equivalent:

OBO Syntax	OWL (Manchester Syntax)	First Order Logic
[Term]		$\forall a, t: \mathbf{inst}(a, A, t) \rightarrow$
id: A	$A \text{ subClassOf } \mathbf{rel} \text{ some } B$	$\exists b: \mathbf{inst}(b, B, t) \wedge$
relationship: $\mathbf{rel} B$		$\mathbf{rel}(a, b, t)$

This suggestion also retains standard transitivity semantics of OWL, so that quantification over time maintains transitivity of the relation in question. This can be shown, e.g. for the transitive relation **hasPart**: if an organism has some heart at any time, and if this heart has some heart valve at any time, then the organism has some heart valve at any time:

$$[A \text{ subClassOf } \mathbf{hasPart} \text{ some } B] \wedge [B \text{ subClassOf } \mathbf{hasPart} \text{ some } C] \rightarrow [A \text{ subClassOf } \mathbf{hasPart} \text{ some } C]$$

And while there is nothing to be gained by actually modifying OWL 2 to use this interpretation, it is very important that ontology engineers are aware of the implications of their modelling decisions with regard to relations that are sensitive to the issue of temporal strength. However, this approach unfortunately would have the consequence that “*temporary relatedness*” cannot be expressed directly in an OWL 2 ontology, so we need to look for more involved solutions to the problem.

4. Temporally Qualified Continuants

4.1. Reification

A common strategy to work around the limitations of description logics is to represent ternary relations through *reification*. Reification involves the introduction of a class $C_{\mathbf{rel}}$ for each ternary relation \mathbf{rel} . The relata of \mathbf{rel} are then connected to instances of $C_{\mathbf{rel}}$ by three new binary relations $\mathbf{R}_1, \mathbf{R}_2, \mathbf{R}_3$. The instance-level assertion

$$\mathbf{rel}(a, b, t)$$

would then be transformed into the following set of assertions:

$$C_{\mathbf{rel}}(x), \mathbf{R}_1(x, a), \mathbf{R}_2(x, b), \mathbf{R}_3(x, t)$$

Such proposals have, with a varying degree of sophistication, seen quite a bit of dissemination in the ontology engineering community [12], but they suffer from significant drawbacks. Most obviously, they are rather complex, which increases the risk of modelling errors and decrease reasoning efficiency [13]. To address the complexity problem, it has been suggested to select reification classes based on what seems ontologically “fitting” for the domain of an ontology [14].

In fact, what seems to be artificial reification from one perspective could even be perceived as ontologically sound representation from a different viewpoint. We might, for example, compare the ternary relational statement

transforms (*Aconitase*, *Citrate*, *Isocitrate*)

with the expression

TransformationProcess and
hasParticipant some *Aconitase* and
hasInput some *Citrate* and
hasOutcome some *Isocitrate*

and judge upon superficial inspection that the later is a reification of the former (where “*TransformationProcess*” is introduced as a class to represent “**transforms**”). But if one commits to the position that it is useful and ontologically sound to accept the category of processes into an ontology, the “reified” translation might actually be the proper representation of the ontological fact, i.e. that there is a transformation process going on whenever aconitase transforms citrate to isocitrate. The relational expression is true only in virtue of the existence of the process. Our goal will thus be to find a reification strategy that is compatible with our ontological commitments.

4.2. *Continuant Stages*

Bittner and Donnelly suggest an ontologically fitting form of reification of temporally indexed parthood relations that allows distinguishing between time-dependent and time-independent parthood relations without referring explicitly to time [15]. For this purpose, they introduce the concept of “stages”, understood as instantaneous spatial entities in the sense that they are confined to a single “time-slice” of a continuant. Therefore a relation between a stage and whatsoever other entity is never ambiguous with regard to time, because it only exists at the moment the stage exists. Stages allow for the distinction between temporary and permanent relatedness, though the scope of the proposal was restricted to the analysis of mereological relations between entities or their stages respectively:

x is a **temporary part of** y iff there exists a stage of x which is **partOf** a stage of y.

x is a **permanent part of** y iff every stage of x is **partOf** a stage of y.

However, we see no reason not to extend this approach to *all* ternary relations that involve continuants and are sensitive to ambiguities because of different temporal strengths: stages allow for the distinction between temporary and permanent

relatedness for a wide variety of relations, but this explicitly excludes binary relations between continuants or their stages that carry implicit reference to time and do not need this kind of treatment. For example

Apple subClassOf **derivesFrom** some *AppleSeed*

is not in need of a temporalised re-interpretation because **derivesFrom** should, in its definition, already specify the temporal order of the relata. The derived entity, that is, needs to temporally succeed the entity from which it is derived.

4.3. *Ontological Status of Stages*

The distinction between a continuant and its stage needs to be distinguished from a similar approach that is taken by the GFO top-level ontology. In GFO, instead of continuants that are present as a whole at every point in time of their existence, there are “presentials” which are present as a whole at exactly one point in time, thus being analogous to stages. The diachronic identity that is a key characteristic of a continuant is then obtained by postulating that for every individual continuant (in non-GFO parlance) there exists a certain universal (a “persistant”) that is instantiated only by a temporally contiguous set of presentials, one for every point in time [3]. In our eyes, this approach is not very attractive for two reasons: it is at odds with the strong intuition that *individual* continuants such as human beings exist, and, second, it requires multiple levels of universals to account for conventional class level assertions, something that might only be acceptable to a *very* limited degree, if at all.²

Regarding relations of different temporal strength, GFO has adopted an approach where relations are reified as “relators” which serve as contexts that aggregate the relata as “players” of certain “relational roles” [17]. Additionally, GFO accounts for different temporal modes of relatedness precisely by distinguishing between presentials and persistants.

We thus need to consider the proper ontological status of stages carefully, especially since there are alternative interpretations available that could also make Bittner and Donnelly's strategy successful. First, stages could be regarded as instantaneous “slices” of continuants. But they could also be seen as (instantaneous or extended) occurrents or as extended phases of continuants, which are referred to in natural language by so-called “phase sortals”, like “larvae” or “child”. Such phases of continuants persist during some sub-period of their “super-continuant” existence: a child and a human being can be the very same continuant, but the temporal duration of the life a human being may extend beyond the temporal duration of the life of the child.

When thinking of stages as occurrents, we would equate them to entities such as “the second trimester of a pregnancy” or “adulthood”. This is a natural choice for ontologies that subscribe to four-dimensionalism, such as the GFO. Here “stages” could just be temporal parts of four-dimensional entities, something that is also proposed by Welty and Fikes in their treatment of temporalised relations [6]. There are some problems with this approach, though. First, while we accept the importance of four-dimensional entities in ontologies, we have reservations against the variety of

² Armstrong [16], for example, believes that higher order universals are only justified if they pertain to formal characteristics of an universal.

four-dimensionalism that reduces all facts about continuants to facts about occurrents. It is a counter-intuitive and revisionary doctrine we do not want to force upon users of top-level ontologies. And secondly, this interpretation of stages would be quite at odds with conventional ways to specify relations. For example, consider that the conventional **partOf** relation holds between physical objects. If we subscribe to the view that stages are temporal parts of objects (hence occurrents), we would have to say that parthood can hold either between continuants or between occurrents – which seems to eliminate the distinction between spatial and temporal parts.

If we, on the other hand, think of stages as the ontological counterparts of “phase sortals” [18], we can avoid this problem. Since phase sortals are used to refer to continuants at some period of their existence, the corresponding entities are still continuants. For example, “child” and “adult” can both characterise the same continuant, but at different times. Also, since phase sortals are important in their own right, it would be tempting to integrate our solution for temporary relatedness with an account of phase sortals. In fact, this can be done by using the BFO account of projections that link SNAP entities (continuants) and SPAN entities (occurrents) [19]: every continuant *c* can be mapped to a corresponding occurrent (its “life”). We can then obtain the entity referred to by the phase sortal by projecting a temporal part of the life of *c* back onto the spatial realm.

If it is construed this way, the projected entity will appear as an additional individual in the OWL model. From the point of view of ontological parsimony, this might not be desirable because the entities described by phase sortals do not really constitute anything over and above the continuant. However, this is a consequence of the reification approach that is unfortunately unavoidable. We will thus prefer the term “temporally qualified continuant” to indicate that we do not intend to hypostatise these entities. It is sufficient to consider “phase sortal talk” as a *façon de parler*, which is effectively talk about the continuant during a certain period of its life or history. For example, “human under 18 years” would be a temporal qualification of the class “human”. While this approach may include both temporally extended and non-extended “slices” of continuants, it seems to be a bit more natural than the “stages” of Bittner and Donnelly and avoids potential terminological confusion about the word “stage”, which might just as well refer to an occurrent (e.g. the early stage of a disease course).

With these clarifications in mind, we now revisit the notions of temporary and permanent relatedness introduced above with regard to temporally qualified continuants.

4.4. Temporary Relatedness

The relation **hasTemporalQualification** (inverse: **temporalQualificationOf**) relates a continuant with a temporal qualification of itself. E.g.,

'Apple_{ABC} at t_{123} ' is a **temporalQualificationOf** Apple_{ABC}

'Greenness_{AppleABC} at t_{123} ' is a **temporalQualificationOf** Greenness_{AppleABC}

Let us consider two classes of continuants *A* and *B* and assume that each instance of *A* has a temporal qualification that is related to some temporal qualification of an instance of *B*:

$$\forall a: \mathbf{inst}(a, A) \rightarrow \exists p, b, q: \mathbf{inst}(p, \mathit{TemporallyQualified}A) \wedge \mathbf{inst}(b, B) \wedge \\ \mathbf{inst}(q, \mathit{TemporallyQualified}B) \wedge \\ \mathbf{temporalQualificationOf}(p, a) \wedge \mathbf{rel}(p, q) \wedge \\ \mathbf{temporalQualificationOf}(q, b)$$

In description logics:

$$A \text{ subClassOf } \mathbf{hasTemporalQualification} \text{ some} \\ (\mathbf{rel} \text{ some } (\mathbf{temporalQualificationOf} \text{ some } B))$$

Similarly, relations between continuants and occurrents can be construed using temporal qualifications. For instance, every A could be related to the part of an occurrent O which occurs during the time of the qualification:

$$\forall a: \mathbf{inst}(a, A) \rightarrow \exists p, o, q: \mathbf{inst}(p, \mathit{Stage}) \wedge \mathbf{inst}(o, O) \wedge \mathbf{inst}(q, O) \wedge \\ \mathbf{temporalQualificationOf}(p, a) \wedge \mathbf{rel}_p(p, q) \wedge \\ \mathbf{processPartOf}(q, o)$$

In description logics:

$$A \text{ subClassOf } \mathbf{hasTemporalQualification} \text{ some} \\ (\mathbf{rel}_p \text{ some } (\mathbf{processPartOf} \text{ some } O))$$

Wherever some temporally qualified continuant related by **rel** to some other entity c , also the unqualified is **rel**-related to c , though not necessarily in the same sense, therefore,

$$\forall a, b, c: \mathbf{rel}^*(b, c) \wedge \mathbf{hasTemporalQualification}(a, b) \rightarrow \mathbf{rel}(a, c)$$

One can then ask how precisely we are to interpret **rel** and **rel*** (and **rel_p** and **rel_p*** respectively) in terms of the interpretations we presented earlier. Clearly, we want to assume standard semantics for **rel** so that the temporally qualified continuant is at all times related to c .

rel* on the other hand obtains between a continuant that has a temporal qualification that is at all times related to c and c , hence it can only establish temporary relatedness (I) between the two entities. We thus, for now, can formulate the following role chains in DL, introducing the new relation **rel-at-some-time**:

$$\mathbf{hasTemporalQualification} \text{ o } \mathbf{rel} \text{ subrelationOf } \mathbf{rel-at-some-time}$$

These can be used to simplify the above expressions to:

$$A \text{ subClassOf } \mathbf{hasTemporalQualification} \text{ some } (\mathbf{rel} \text{ some } B)$$

or simply

$$A \text{ subClassOf } \mathbf{rel-at-some-time} \text{ some } B$$

Assuming **rel** is transitive, as is for example **hasPart**:

$A \text{ subClassOf } \mathbf{hasTemporalQualification} \text{ some } (\mathbf{rel} \text{ some } B)$

$B \text{ subClassOf } \mathbf{hasTemporalQualification} \text{ some } (\mathbf{rel} \text{ some } C)$

there is now no way to infer:

$* A \text{ subClassOf } \mathbf{hasTemporalQualification} \text{ some } (\mathbf{rel} \text{ some } C)$

This is consistent with the fact that, e.g. an apple *a* is part of a tree *t* at *t*₁, and the same apple, at *t*₂, after being no longer part of *t* has a germ *g*, then *g* is not part of *t* at any time.

4.5. Permanent Relatedness

Permanent relatedness of two entities can be formulated both from the perspective of their temporal qualifications and from the vantage point of the entire temporally persisting entities. For qualifications, one would express the fact that every qualification of *A* is related to some *B*-qualification as follows:

$$\begin{aligned} \forall a, p: & \mathbf{inst}(a, A) \wedge \mathbf{inst}(p, \mathbf{TemporalQualificationOf} A) \wedge \\ & \mathbf{temporalQualificationOf}(p, a) \rightarrow \\ \exists b, q: & \mathbf{inst}(b, B) \wedge \mathbf{inst}(q, \mathbf{TemporalQualificationOf} B) \wedge \mathbf{rel}(p, q) \wedge \\ & \mathbf{temporalQualificationOf}(q, b) \end{aligned}$$

Or, in description logics:

$\mathbf{temporalQualificationOf} \text{ some } A \text{ subClassOf } \mathbf{rel} \text{ some } (\mathbf{temporalQualificationOf} \text{ some } B)$

From the perspective of the unqualified continuants, we want to claim that an instance of *A* has only qualifications that are **rel**-related to instances of *B*, which in DL notation and taking into account possible empty universal quantification reads as follows (the last conjunct includes the formula above):

$A \text{ subClassOf } (\mathbf{hasTemporalQualification} \text{ only } (\mathbf{rel} \text{ some } (\mathbf{temporalQualificationOf} \text{ some } B)) \text{ and } (\mathbf{hasTemporalQualification} \text{ some } (\mathbf{rel} \text{ some } \mathbf{temporalQualificationOf} \text{ some } B)))$

Either formulation preserves transitivity if the basic relation **rel_t** is transitive:

$\mathbf{temporalQualificationOf} \text{ some } A \text{ subClassOf } \mathbf{rel_t} \text{ some } (\mathbf{temporalQualificationOf} \text{ some } B)$

$\mathbf{temporalQualificationOf} \text{ some } B \text{ subClassOf } \mathbf{rel_t} \text{ some } (\mathbf{temporalQualificationOf} \text{ some } C)$

temporalQualificationOf some *A* subClassOf **rel_t** some
(temporalQualificationOf some *C*)

Since permanent relatedness is considered to be the default in OWL 2 ontologies, having to formulate permanent relatedness this way is rather unfortunate. Not only does it place a large burden on the ontology engineer, but it also breaks “upgrading” ontologies to new versions of the top-level that include an account of temporal qualifications. Thus, ideally, we want to impose restrictions on the potential temporal qualifications of a class of continuants based on the following axiom:

A subClassOf **rel** some *B*

This can be achieved by using axioms like the following for every relation **rel** as need be:

rel some owl:*Thing* EquivalentTo
hasTemporalQualification only (**rel** some owl:*Thing*)

This definition (where owl:*Thing* should be substituted with the correct domain and range of **rel**) ensures that the relation is properly inherited by all qualifications of a continuant, if it has any. Since it is usually recommended to define all necessary relations in a top-level ontology [11], this work would only have to be done once and would not be a burden to users of the top-level.

5. Conclusion

We have shown that when expressing relationships between continuants, ontology engineers cannot safely ignore the dynamic nature of reality without introducing unnecessary ambiguity or even factual errors into ontologies. Since we acknowledge the importance of temporary relatedness, we cannot simply accept an informal reinterpretation that all OWL 2 relations imply permanent relatedness. Instead, we provide a formalisation that relies on making assertions about temporally qualified continuants, representing continuants as they are viewed within a restricted temporal context. This introduces an element of reification into the ontology, where some individuals in the OWL models do not correspond to proper entities of ontological value. Still, it does operate within the confines of the ontological framework of BFO, where both occurrents and continuants are useful and irreducible entities.

Unlike other reification schemes our proposal does not impose unnecessary complexity on the ontology engineer, since it allows the user to use the unqualified object property (e.g. **rel**) for permanent relatedness, and the combination of **hasTemporalQualification** and the property in question to express temporary relatedness. Thereby, it provides a compelling trade-off between semantic accuracy and complexity. With regard to its complexity and efficiency two points still need to be evaluated:

- We include **temporalQualificationOf** and **hasTemporalQualification** as object properties which are marked as functional or inverse functional respectively. In an

application ontology, these will be used extensively, which might cause some performance penalty for reasoning.

- We specify property chains for all relations included in the ontology. This effectively turns them into composite properties as per section 11 of the OWL 2 structural specification, which also imposes the restriction that composite properties are not to be used in cardinality restrictions [10]. Since the pattern described here is suggested for inclusion into a top-level ontology, this imposes a significant additional expressivity limit on unsuspecting users, the impact of which should be carefully evaluated.

Still, it was possible to show that support for temporary relatedness can be layered upon existing OWL 2 semantics in a user-friendly and ontologically minimally offensive way. In the present paper, we have presented the crucial relation **hasTemporalQualification** as primitive and only given an informal explanation of its meaning. It would be desirable to give a more specific account of it in the future, by, for example, using the formal tools provided by BFO.

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