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

# Introduction

This paper addresses an ontological-logical puzzle that has been arisen in the Open Biomedical Ontologies (OBO) community and in the current BFO2 redesign project. However**,** it seems to be of general interest**,** as it addresses a weakness of all OWL ontologies that link continuant entities by binary relations (OWL object properties) . Just as most application ontologies OBO embraces three-dimensionalism as its ontological framework**,** introducing a top level distinction between continuants and occurrents**,** or endurants vs. perdurants**,** 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.

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 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 continuants not only persist**,** but also continuously change over time. The shape and the constitution of biological organisms are in continuous flux. They continuously gain and lose parts**,** qualities**,** and dispositions. 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. The ternary instantiation relation **inst³** relates an individual to a type at a time.

*A ripening apple:*

a**,** b**,** t**,** t1: **inst³** (*Apple***,** a**,** t) **inst³** (*Green***,** g**,** t)  **inst³** (*Apple***,** a**,** t1)   
**inst³** (Red**,** r**,** t1)  **bearerOf** (a**,** g**,** t)  ¬ **bearerOf** (a**,** g**,** t1)   
  ¬ **bearerOf** (a**,** r**,** t)  **bearerOf** (a**,** r**,** t1)   
  
*Situation before and after a heart transplant*

a**,** b**,** t**,** t1: **inst³** (*Heart***,** a**,** t) **inst³** (*Body***,** b**,** t)  **inst³** (*Heart***,** a**,** t1)   
**inst³** (*Body***,** b**,** t1)   
 **partOf** (a**,** b**,** t)  ¬ **partOf** (a**,** b**,** t1)

In these examples continuants of different kinds are related at different time instants. But time-indexed relations are also relevant when connecting continuants with processes:

*The soprano Mary participating in a performance of Beethoven’s* *th symphony****,*** *during the 4th movement only:*

not (**participatesIn** (Mary**,** Beethoven\_th\_Symphony\_Performance\_1234**,** 2012-01-01:20:05) )   
**participatesIn** (Mary**,** Beethoven\_th\_Symphony\_Performance\_1234**,** 2012-01-01:20:55)

As we see**,** a time index is necessary for many statements 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 etc.

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 will have difficulties if the modelling is not intuitive. This a major reason why four-dimensionalism**,** regardless of the philosophical merits**,** 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. OWL DL is also the favourite formalism embraced by the OBO community.

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]. Time-indexed relationships have been introduced as instance-level relations into the OBO Relation ontology []. In the current work on a new release of the Basic Formal Ontology**,** BFO 2**,** ternary (time-indexed) instance-level relations have also been proposed expressed in first order logics.

The question we address in this paper is whether the favoured three-dimensionalist approach is reconcilable with the requirements of representing knowledge about changing relationships between entities. We will analyse the consequences of this for the creation of a compatible OWL version of BFO 2. The paper is organized as follows: we specify the assumptions we make about the three-dimensional framework that is used as a basis to represent change over time. This is done in first order logic. We then extend that framework by introducing temporally qualified continuants**,** and show how binary relations between temporally qualified continuants can be defined based on the underlying relationships between continuants as vehicle to express change in OWL. In a first glance**,** these entities might look like four-dimensional entities in sheep's-clothing. However**,** we will show that these temporally qualified continuants are just introduced as *façon de parler***,** and thus are ontological innocuous.

# Basic notions

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 **rel³** (a**,** b**,** t) with explicit time index**,** the ontology engineer faces the problem how to express it due to the limitations of OWL**,** using a binary object property **rel².** Ignoring this problem**,** ambiguous interpretations arise**,** as exemplified in the following class expression (as expressed in Manchester Syntax [7]) :

*A* subClassOf **rel²** 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 **inst³** is the time-indexed instantiation relation that holds between an individual and a class at some time t) . The relation **within** is temporal inclusion. Temporal inclusion for temporal instants is true if and only if they are the same instant; temporal inclusion for temporal regions is as expected.

We here define three temporal strengths, viz. temporal relatedness, permanent generic relatedness and permanent specific relatedness:

*TemporallyRelated* (*A***,** *B*) =def at: [**inst³ (***A*, a, t)   
  b**,** t1: (**inst³** (*B***,** b**,** t1)  **rel³** (a**,** b**,** t1)  **within** (t1**,** t)) ]

Informally: for all a instances of *A* there is some time t and some instance b of *B* such that a is related to b at t. Examples: (a) for all apple seeds there is some apple such that the seed is part of the apple at some time. (b) for all trees there is some leaf such that the leaf is part of the tree at some time.

*PermanentGenericallyRelated* (*A***,** *B*) =def at: [**inst³ (***A*, a, t)   
  b: [**inst³** (*B***,** b**,** t)  **rel³** (a**,** b**,** t)) ]

Informally: for all a instances of *A* there is**,** at all times t that a exists**,** some instance b of *B* such that a is related to b at t**,** but not necessarily always the same b at all times t. Examples: all cells have a water molecule as part at all times**,** but not always the same water molecule.

*PermanentSpecificallyRelated* (*A***,***B*) =def at1: [**inst³ (***A*, a, t1)   
  b: [**inst³** (*B***,** b**,** t1)  **rel³** (a**,** b**,** t1)    
 t: (**inst³** (*A***,** a**,** t) **rel³** (a**,** b**,** t) **inst³ (***B***,** b**,** t)) ) ]

Informally**,** for all a instances of *A* there is**,** at all times t that a exists**,** an instance b of *B* such that a is related to b at t; in this case it is always the same b at all times t. Examples: a human being has a brain as part at all times**,** and it is necessarily the same brain.

Our working hypothesis will be that both interpretations**,** *“temporary relatedness” (*I) and *“permanent relatedness” (*II) are relevant in the context of application ontologies. It is still subject to debate to what extent the distinction between specific and generic relatedness matters. 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**,** the second**,** largely extended release being under current development. Nevertheless the proposal sketched here could potentially be implemented in other top-level ontologies that are sufficiently similar to BFO.

# Connection to the SNAP/SPAN distinction

BFO has traditionally maintained a strong distinction between 3D and 4D accounts of reality [ ]. 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 continuant and the occurrent views represent complementary perspectives. 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**,** O0 and O1**,** each describing whether the relation **rel** holds between two objects a and b at different points in time. Now**,** if in O0 “**rel (**a**,** b) ” is true**,** and in O1**,** “**rel (**a**,** b) ” is false**,** we derive a contradiction once we construct a SPAN ontology Os that references both O0 and O1**,** 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.

# Conventional Modellers’ Strategy for Temporalised Relations in OWL 2

As explicit semantics for modelling temporal dynamics are not available in OWL 2**,** modellers tend to 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 [] 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. This is even more significant as this does not constitute at all a side issue or an idiosyncrasy of biomedical ontologies. On the contrary**,** virtually all OWL ontologies contain axioms on classes of continuants using binary object properties and leave the exact interpretation unexplained.

To address this mismatch and try to understand it better we sketch here a possible solution which consists in a modification of the interpretation function. 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 conditionalized 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  **,** interpretation I) :

t (a I**,** t)   I   (aI **,** t)  *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**,** both of which 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* **rel²** some *B*) :

ObjectSomeValuesFrom (**rel²,** *B*) I =def { (a**,** t)   I | b: (a**,** b**,** t)  **rel³**I  (b**,** t)  *B*I}

Value restriction (A **rel²** only B) :

ObjectAllValuesFrom (**rel²,** *B*) I =def { (a**,** t)   I | b: (a**,** b**,** t)  **rel³**I  (b**,** t)  *B*I }

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

ObjectPropertyAssertion (**rel²,** a**,** b) I =def t (a I**,** t)   I   (aI**,** bI**,** t)  **rel³**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]  id: *A*  relationship: **rel²** *B* | *A* subClassOf **rel²** some *B* | a**,** t: **inst³** (*A***,** a**,** t)   b: **inst³** (*B***,** b**,** t)    **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* subClassOf **hasPart** some *B*] ∧ [*B* subClassOf **hasPart** some *C*] →  
[*A* subClassOf **hasPart** 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.

Furthermore**,** an OWL instance level assertion using **rel²** would be problematic**,** as the OWL expression

a **rel²** b

would also have to be interpreted in FOL terms as

a**,** b**,** t: **rel³** (a**,** b**,** t)

which is the weakest possible statement on two individuals a and b with regard to the relation **rel** and time. This contrasts with the above formalized object property assertion.

# Temporally Qualified Continuants

## 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***rel**for each ternary relation **rel**. The relata of **rel** are then connected to instances of *C***rel**by three new binary relations **R1, R2, R3**. The instance-level assertion

**rel³ (**a**,** b**,** t)

would then be transformed into the following set of assertions:

C**rel (**x) **, R1 (**x**,** a) **, R2 (**x**,** b) **, R3 (**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. This bears the risk of errors in the ontology engineering process and decreases 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.

## 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

*AppleTree* 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. Another example is the relation between dependent continuants and independent ones as they always span across the whole existence of the further: the redness of a given apple is the redness of this apple at all times.

## 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) a certain universal (a “persistant”) exists 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]](#footnote-3)

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**,** so-called "phase sortals" like “larva" or “child”. Such phases of continuants persist during some sub-period of their “super-continuants” 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 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 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” or "history") . 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 10 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.

# A 3-D Theory of temporally qualified continuants (Fabian & Janna)

A temporally qualified continuant (TQC) is a way of referring to a continuant during a portion of time. It is therefore a tuple a**,** t where ais an instance of a continuant and t is a portion of time. We will use x**,** y**,** z to indicate TQCs.

There are several axioms needed to link TQCs to the continuants that they are temporal slices of and to ensure that TQC portions of time do not exceed the allowed portion of time that the corresponding continuant instance spans over. Instantiation of a TQC is thus not time-indexed**,** while normal instantiation of continuants is time indexed as in the examples above. To distinguish these two different instantiation predicates**,** we will introduce **inst²** to denote the non-time-indexed variant**,** corresponding to Type in OWL Manchester syntax.

We will use the notation *TQCA* to denote the class of temporally qualified continuants which range over continuants of type A.

x : [**inst²** (*TQCA***,** x)  a**,** t**,** t1: (**inst³** (A**,** a**,** t)  **equals** (x**, 〈**a**,** t1**〉**) **within** (t1**,** t)) ]

The intended meaning of the predicate **equals** is identity**.**

We further introduce a relation **continuantOf** to link a TQC to the continuant that it is a TQC of. That is**,**

x : [**inst²** (*TQCA***,** x)  a**,** t: (**inst³** (*A***,** a**,** t)  **continuantOf** (a**,** x)) ]

Now**,** for the remainder of this document**,** we will use the relationship **rel²** to represent a non-time-indexed relationship linking TQCs**,** and **rel³** to represent a normal BFO time-indexed relation. Our project will be to show that we can faithfully express different temporal strengths of time-indexed BFO relations by means of the logical machinery we have here introduced.

In the next sections, we will discuss the representation of the three different temporal strengths, linking from the standard representation in BFO FOL through the introduction of temporally qualified continuants to the standard representation in OWL, showing how these different temporal strengths can be implemented through this method in a binary relationship framework such as OWL.

## Temporary Relatedness

We begin with the definition given above for temporary relatedness between two continuants, using a relationship **rel³**. We then insert temporally qualified continuants and derive the form that the relationship takes for temporally qualified continuants and a binary relationship **rel²**. This binary relationship can be mapped to OWL axioms, which we describe thereafter.

at : [**inst³** (*A*, a, t)  b**,** t1 : (**inst³** (*B*, b, t1)  **rel³** (a, b, t1)  **within** (t1, t)) ]

Transposing a, t with an instance of a temporally qualified continuant x = a, t, where **continuantOf (**a, x) , and similarly for b, t1 and y, we get:

at : [**inst²** (*A*, a, t)    
 bt1 : (**inst²** (*B*, b, t1)  **rel² (**a, t1, b, t1)  **within** (t1, t)) ]

x : [**inst²** (TQCA, x) 

ayz : (**inst² (***TQCA*, y)  **inst² (***TQCB*, z)   
 (**continuantOf (**a, x)  **continuantOf (**a, y))  **rel²** (y, z) ]

This means that the logical form of the expression of temporary relatedness is that at least one temporally qualified `slice' of A is related to some temporally qualified. 'slice' of B.

However, we need another axiom to constrain **rel²** in the above to ensure that the portions of time are appropriately overlapping, since **rel³** holds at one time only:

xy : [**rel²** (x, y)  abtt1 : (**equals** (x, a, t)  **equals (**y, b, t1)   
 **continuantOf (**a, x)  **continuantOf (**b, y)  **rel³ (**a, b, t1)  **within** (t1, t)) ]

Now we have derived a binary expression of **rel** we are free to use this in OWL axioms. We introduce the relation **hasSameContinuant** between temporally qualified continuants to express that they are TQC slices of the same continuant, expressed in the above axiom (??) as (**continuantOf (**a, x) **continuantOf (**a, y)), which allows us to express temporary relatedness in OWL as follows:

*TQCA* subClassOf **hasSameContinuant** some (**rel²** some *TQCB*)

In other words, some temporally qualified slice of A is related to some temporally qualified slice of B. But this makes a claim about the class *TQCA*, while we would ideally like to say something about the target continuant classes A and B in our OWL version, for ease of use by the end user. Thus, we introduce a new relationship, **relTemp**, that obtains between continuants, and should be interpreted as follows:

*A* subClassOf **relTemp** some *B*   
*TQCA* subClassOf **hasSameContinuant** some (**rel²** some *TQCB*)

(Here, we assume the availability of either a rules engine to perform the 'interpretation' or a macro expansion engine.)

## Permanent Generic Relatedness

Permanent generic relatedness is considered by some to be the most common interpretation of temporally unspecified relations in biology. We earlier gave the axiom for this in FOL as:

at : [**inst³** (*A*, a, t)  b : (**inst³** (*B*, b, t)  **rel³** (a, b, t))]

Factoring out the time index as we did before by introducing temporally qualified continuants, this transforms into:

at : [**inst²** (*A*, a, t)  b : (**inst²** (*B*, b, t)  **rel²** (a, t, b, t))]

And introducing instances of temporally qualified continuants as before, that becomes:

x : [**inst²** (*TQCA*, x)  y : (**inst²** (*TQCB*, y)  **rel²** (x, y))]

This is the easiest and most elegant translation case from the FOL perspective. Moving to OWL, the above axiom (??) appears as:

*TQCA* subClassOf **rel²** some *TQCB*

Again, we need to introduce a new relationship to make this case explicit and make use of a translation rule or macro expansion to bridge back to the underlying relationship. We introduce **relPermGen**:

*A* subClassOf **relPermGen** some *B*  *TQCA* subClassOf **rel²** some *TQCB*

## Permanent Specific Relatedness

Finally, we consider the case of permanent specific relatedness. This is actually the most difficult to express in FOL and then translate via the above mechanism to statements about temporally qualified continuants that can be expressed in OWL, since it requires the additional axiom to ensure that it is always the same instance that is related. But let us start again with the definition that we gave for permanent specific relatedness above:

at1 : [**inst³** (*A*, a, t1)  b : (**inst³** (*B*, b, t1)   
t : (**inst³** (*A*, a, t)  (**rel³** (a, b, t)  **inst³** (*B*, b, t)) ) ]

Following the route we used before, we push the time index into a tuple, as follows:

at1: [**inst²** (*A*, a, t)    
 b: (**inst²** (*B*, b, t) t: (**inst²** (*A*, a, t)  (**rel²** (a, t, b, t) **inst²** (*B*, b, t)))]

The tuples can be replaced with instances of temporally qualified continuants as before, but in this case, we need to introduce a few additional points to the axiom:

x : [**inst²** (*TQCA*, x)    
y : (**inst²** (*TQCB*, y)  **rel²** (x, y) x1, a : (**inst²** (*TQCA*, x1)    
 **continuantOf** (a, x)  **continuantOf** (a, x1) 

y1, b : (**inst²** (*TQCB*, y1)  **continuantOf** (b, y)    
 **continuantOf** (b, y1) **rel²** (x1, y1))))]

This is quite tricky to express in OWL, but we attempt it as follows, again using the **hasSameContinuant** relationship introduced before:

*TQCA* subClassOf **rel²** some *TQCB* and   
 (**hasSameContinuant** only   
 (**rel²** some (**hasSameContinuant** some *TQCB*)))

The two uses of hasSameContinuant attempt to `constrain' the actual instances of *A* and *B* to be the same one in all cases. We can (and should) hide that complexity behind a neat relationship introduced, say, as **relPermSpec**, such that:

*A* subClassOf **relPermSpec** some *B*    
 *TQCA* subClassOf **rel²** some *TQCB* and

(**hasSameContinuant** only (**rel²** some (**hasSameContinuant** some *TQCB*)))

TODO:

* Temporally-qualified continuants as *façon de parler*
* prove that **rel²** is transitive in the axiomatization if the underlying **rel³** was transitive, and it might be useful to think about the other sorts of properties that relations can have and do have in the BFO theory.
* The actual macro expansion or rules mechanism for the OWL needs to be determined.
* We should still extend this into a treatment of relations between continuants and occurrents (e.g. participation during). Finally we should populate the above with some worked `standard' examples e.g. parthood.

# OWL model from original manuscript (Stefan)

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:

*A* subClassOf **continuantOf** some   
 (**rel²** some (**hasContinuant** some *B*))

Similarly**,** relations between continuants and occurrents can be construed using temporal qualifications. For instance**,** every *A* could be related by the relation **relo²** to an occurrent *O* which occurs during the time of the qualification:

*A* subClassOf **continuantOf** some (**relo²** some *O*)

Wherever some TQC x related by **rel²** to some other TQC y**,** the latter qualifying the continuant c**,** we introduce axiomatically:

xyc:   
 **inst²** (TQC, x)  **inst²** (TQC, y) **rel**² (x**,** y)  **continuantOf** (c**,** y)  **rel²** (a**,** c)

Here, the binary relation **rel²** is still justified, because the time instant is attached to the first relatum a.

One can then ask how precisely we are to interpret **rel²** and **relo²** in terms of the interpretations we presented earlier. Clearly**,** we want to assume standard semantics for **rel²** so that the temporally qualified continuant is at all times related to c.

**rel²** 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 **reltemp**:

**continuantOf** o **rel²** subrelationOf  **relTemp**

These can be used to simplify the above expressions to:

*A* subClassOf **continuantOf** some (**rel²** some *B*)

or simply

*A* subClassOf **reltemp** some *B*

Assuming **rel²** is transitive**,** as is for example **hasPart²**:

*A* subClassOf **continuantOf** some (**rel²** some *B*)

*B* subClassOf **continuantOf** some (**rel²** some *C*)

there is now no way to infer:

\* *A* subClassOf **continuantOf** some (**rel²** some *C*)

This is consistent with the fact that**,** e.g. an apple a is part of a tree t at t1**,** and the same apple**,** at t2**,** after being no longer part of t has a germ g**,** then g is not part of t at any time.

## 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:

**hasContinuant** some *A* subClassOf **rel²** some (**hasContinuant** 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 subClassOf (**continuantOf** only (**rel²** some (**hasContinuant** some B)) and  
 (**continuantOf** some (**rel²** some **hasContinuant** some B)))

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

**hasContinuant** some *A* subClassOf **reltrans** some   
 (**hasContinuant** some *B*)

**hasContinuant** some *B* subClassOf **reltrans** some   
 (**hasContinuant** some *C*)

——————————————————––––––––––––––––––––––––––––––  
**hasContinuant** some *A* subClassOf **reltrans** some   
 (**hasContinuant** 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 **rel²** some *B*

This can be achieved by using axioms like the following for every relation **rel²** as need be:

**rel²** some owl:*Thing* EquivalentTo   
 **continuantOf** only (**rel²** some owl:*Thing*)

This definition (where owl:*Thing* should be substituted with the correct domain and range of **rel**) ensures that the relation is inherited by all qualifications of a continuant**,** if it has any. It prevents at least some potential errors. 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.

# 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. **rel²**) for permanent relatedness**,** and the combination of **continuantOf** 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 **continuantOf** and **continuantOf** 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 **continuantOf** 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.

Acknowledgements

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REVIEWS

----------------------- REVIEW 1 ---------------------

PAPER: 67

TITLE: Expressing time-dependent relations through temporal qualifications

AUTHORS: Niels Grewe, Janna Hastings, Ludger Jansen, Chris Mungall, Alan Ruttenberg and Stefan Schulz

OVERALL RATING: 1 (weak accept)

The article discusses the hardships in representing time-indexed relations with the tools of description logics and proposes a reification strategy for expressing temporary and permanent relatedness through a temporal qualification property pair that relates an entity tout-court to its temporally qualified mirror entity. it is shown how this scheme can overcome the limitations of popular foundational ontologies as well as OWL2 tractable profiles.

The clarity of writing is commendable, with a simple wording and narration which never goes down into banality. Examples on how these temporal qualification schemes apply to mereological relations, such as transitive or intransitive parthood, puts this work in the core area of formal ontology literature.

However, my recommendation is that the authors make clearer where their discussion on existing approaches ends and where their contribution starts, as figuring it out requires some effort. If they do not want to restructure the paper, they should at least end the introductory section with the usual outline paragraph explaining which sections describe their work and which describe the work of others, or at a bare minimum include cross-references.

A state of art overview is also absent, probably due to the unusual narrative chosen. However, important work on time-indexed relations for OWL and OWL2 is missing (cf. [1][2][3]). I recommend the authors to add a separate section that clarifies what stands out in their proposal against existing work.

It could be interesting to provide an insight as to how the pros, cons and possible solutions to the foundational ontologies described could relate to representations of relative time-indexing in non-foundational ontologies. Take for example the timeline ontology [4] which is actively employed in several DBTune Linked Data sets. How would the proposed approaches in the paper apply to properties holding at instants or intervals of an entity's timeline? e.g. temporal relations holding for a media recording per se vs. its playback's timeline?

Most of all, the topic of representing temporal relatedness and the way it is tackled in this paper seems like it would ignite a fruitful and heated discussion in the conference itself. One plus for recommending the paper for acceptance.

A few minor corrections:

- Section 1 : bullet (II) is incorrectly indented and Example should be underlined as it is above

- Section 2 : "continant" -> "continuant"

[1] Giancarlo Guizzardi's work, e.g. Veruska Zamborlini, Giancarlo Guizzardi: On the Representation of Temporally Changing Information in OWL. EDOCW 2010: 283-292

[2] Aldo Gangemi's work, e.g. Gangemi A. Super-duper Schema: an OWL2+RIF DnS Pattern. V. Chaudry (ed.): Proceedings of DeepKR Challenge Workshop at KCAP11, <http://www.ai.sri.com/halo/public/dkrckcap2011/Gangemi.pdf>

[3] LOA's work, e.g. Masolo C., Vieu L., Bottazzi E, Catenacci C., Ferrario R., Gangemi A., Guarino N. “Social Roles and their Descriptions”, in Welty C and Dubois D (eds.), Proceedings of the Ninth International Conference on the Principles of Knowledge Representation and Reasoning (KR2004)

[4] http://motools.sourceforge.net/timeline/timeline.html

----------------------- REVIEW 2 ---------------------

PAPER: 67

TITLE: Expressing time-dependent relations through temporal qualifications

AUTHORS: Niels Grewe, Janna Hastings, Ludger Jansen, Chris Mungall, Alan Ruttenberg and Stefan Schulz

OVERALL RATING: -1 (weak reject)

The discussion this paper provides is interesting, but it is not clear

what the main discussion points of this paper and what the authors want to propose.

----------------------- REVIEW 3 ---------------------

PAPER: 67

TITLE: Expressing time-dependent relations through temporal qualifications

AUTHORS: Niels Grewe, Janna Hastings, Ludger Jansen, Chris Mungall, Alan Ruttenberg and Stefan Schulz

OVERALL RATING: -3 (strong reject)

The paper proposes to adopt two terms, namely 'hasTemporalQualification' and 'temporalQualificationOf', to form OWL class expressions using relations which are typically temporal. The two terms are to be understood intuitively, but not formally nor ontologically, as the relation (and its inverse) between a continuant and one of its stages. However, this should not be understood as having any ontological implication because there is no forthcoming ontological commitment which agree to the authors preferences, it is a mere "facon de parler". The motivation is to remove a diagnosed confusion in users when expressing temporal relations in OWL.

The paper does not meet the conference's standards and if it even remotely made a contribution at all it would nevertheless not be appropriately targeted at FOIS. Thus, my overall recommendation is: strong reject.

While the topic suggested by the title is admittedly at first sight interesting, the paper is extremely disappointing. The paper is a self-sufficient opinion piece culminating in a position statement on what emerges as an anecdotal, if not private, terminological point. The paper lacks scholarship and the proposal is simply ludicrous.

To sum up the overall paper, it starts with submitting to the continuant-occurrent distinction (it is intuitive and agreeable to the authors), apparently ignoring for now that there are other ontological approaches to temporality. There follows platitudes concerning temporal relations, OWL and a number of ontological approaches. The problem of finding an agreeable OWL phrasing is framed against BFO, although Grenon's FOIS-06 using lives a la BFO is not discussed. The Welty&Fikes approach, however, is; but it is 4D and this is sufficient cause for it to be simply waved away as not intuitively fit. The paper is so confident about these intuitions that Welty&Fikes' claim that 4D suits the scientists and 3D commonsense is not even worth countering; a puzzling omission given the importance given by the authors to user intuitions. Contra BFO, the present paper follows a stage theoretical approach (Bittner&Donnelly). Even the stage approach, however, as such, is not agreeable to the

authors, the inconsistency with BFO is waved away: there are no ontological consequences. In the end, the paper offers a terminological variation of the vocabulary of a stage theory and revels in semantic naivete and the absence of ontological considerations.

The reader wonders why the authors own intuitions, even those of the community they have happened to encounter or pretend to represent are so privileged as to have the force of argument, immediate truth and self justification in matter of ontology and formal semantics. The question is particularly striking while going through a fruitless discussion ending with a non event. The 'let me tell you' tone in combination to the lack of scholarship and marked condescension towards the nondescript, so easily confused 'users of top-level ontologies' is alienating even to an otherwise sympathetic reader. The paper not only assumes familiarity but also agreement with the BFO and RO ontologies with little explanation. Despite this fact it seems to argue superficially for a position which is inconsistent with BFO.

The paper contains long platitudinal musings prefatory to the terminological proposal. This introductory material (most of the paper) denotes secondary, superficial grasp if not ignorance, of the issues and field at large. Moreover, ontology is reduced to terminology choices in the face of intuitions. The terminological proposal and conclusion constitute a mockery of the use of OWL.

The paper is an opinion piece and does not meet reasonable standards of academic communication. Claims and assertions are justified by a unique evaluation criterion based on the opinion, intuitions or preferences of the authors (literally).

The terminological proposal is motived by and offered in answer to diagnosed difficulties from users. It is confused and there is little hope of it addressing the alleged motivation. The paper demonstrates naivete and does not only fails to appreciate but simply negates at least two decades of work in knowledge acquisition around the problem of bridging the gap between knowledge engineers and subject matter experts.

1. Corresponding author: Niels Grewe**,** Institute of Philosophy**,** University of Rostock**,** 18051 Rostock**,** Germany. E-Mail: niels.grewe@uni-rostock.de [↑](#footnote-ref-2)
2. Armstrong [16]**,** for example**,** believes that higher order universals are only justified if they pertain to formal characteristics of a universal. [↑](#footnote-ref-3)