Butterflies and Embryos: The Ontology of Temporally Qualified Continuants

Ludger Jansen [1 2], Niels Grewe [2]*

1 Department of Philosophy, University of Münster
2 Institute of Philosophy, University of Rostock

ABSTRACT

Motivation: A serious shortcoming of the Web Ontology Language (OWL), especially for biomedical ontologies, is that it does not allow for other than two-place relations. Some strategies to cope with this problem have been proposed in the literature, which range from temporally qualified relations to slices, phases and stages.

Method: This paper adds temporally qualified continuants (TQCs) as a further strategy that is tailored to work with the 3D centred approach of the Basic Formal Ontology (BFO), but should also be compatible with other top-level ontologies.

Result: The paper discusses various ontological options for the ontology of TQCs and shows how it can be used to express temporal relatedness as well as permanent generic relatedness. However, due to the intrinsic constraints of OWL, permanent specific relatedness cannot be expressed within the expressivity of OWL 2.

1 INTRODUCTION

1.1 Temporal qualification: The OWL problem

An important feature of ontologies is the representation of relations between classes. In the Web Ontology Language (OWL) only binary object properties between individuals are admitted (Motik et al. 2009); these are transformed to class relations by means of universal quantification. This leaves no room for a temporal qualification that would require at least a triadic relation following the general pattern "Class1 subClassOf **isRelatedTo** some Class2 at time T". On the one hand, there is good reason to restrict the subclass hierarchy to such cases that hold at all times because one does not want to include accidental subclass relations anyway. For example, "Material Object subClassOf **hasLocation some** Spatial Region" is true at any time as there can never be a material object that has no location. On the other hand, other relations like **partOf** or **participatesIn** do call for a temporal qualification. More specifically, we have to distinguish the following three cases (elucidated with mereological examples):

- *Permanent specific relatedness:* A bacterium has cell membrane – it is the same membrane over the whole time *of its* existence.
- *Permanent generic relatedness:* A multicellular organism at any time of its existence consists of cells – but not always of the same cells.
- *Temporary relatedness:* A mature instance of the order *Lepidoptera* has a pair of wings, but it did not have this pair at every time of its existence.

If we consider assertions on class level, these three kinds of temporary relatedness match to three typical non-equivalent quantificational structures that can be expressed with the universal and the existential quantifier (the first universal quantifier being due to the semantics of class-level assertions):

- *Permanent specific relatedness:*
  For ALL x there is SOME y such that
  at ALL times t: R(x, y, t)
- *Permanent generic relatedness:*
  For ALL x at ALL times t
  there is SOME y such that : R(x, y, t)
- *Temporary relatedness:*
  For ALL x there is SOME y such that
  at SOME time t: R(x, y, t)

Of these three, permanent specific relatedness is the strongest one. It implies permanent generic relatedness which, in turn, implies temporary relatedness. Combinatorially, two more cases are conceivable. These will, however, rarely be important for the biomedical domain:

- *Permanent universal relatedness:*
  For ALL x at ALL times t it holds
  for ALL y that: R(x, y, t)
- *Temporary simultaneous universal relatedness*:
  For ALL x at SOME time t it holds
  for ALL y that: R(x, y, t)
- *Temporary (possibly sequential) universal relatedness:*
  For ALL x and for ALL y it holds
  at SOME time t that: R(x, y, t)

* To whom correspondence should be addressed.

1.2 Use cases

Typical use cases for temporal qualifications are developmental stages of an organism. E.g., the life of a normal instance of the type *Lepitoptera* is the following: egg, caterpillar, pupa, butterfly. Here we have a good example of an instance of the same biological species passing through these phases. Any instance in the butterfly stage will be diachronically identical with some caterpillar instance some time earlier. Another important use case is embryology and developmental ontologies in general, for terms and distinctions for different developmental phases abound: cygote, embryo, fetus, morula, blastula, gastrula, embryo in the fifth week after conception, conceptus in Carnegie stage 4.

1.3 Previous work

Phase sortals. The terms we mentioned as possible use-cases are normally know under the name of "phase sortals" in Philosophy (Wiggins 1980) or "phased sortals" in Ontology Engineering (Guarino/Welty 2009). A phase sortal is normally defined as "a count-noun such that a given object may fall within its extension at one time but not at another" (van Inwagen 2001, 136). Consequently, the OntoClean method characterizes phased sortals as independent, anti-rigid and supplying identity criteria (Guarino/Welty 2009, 215). In this paper, we explicitly do not deal with the terms as such, but with the entities they refer to and we assume that there are, in fact, entities that phased sortals refer to rigidly, namely temporally qualified continuants.

The standard reading of OWL assertions. The semantic of OWL assertions is to read relational statements as implicitly universally quantified:

- "Heart_valve **subClassOf** part-of **some** Heart" is to be understood as: "<u>For all</u> heart valve instances *a* there is a heart instance *b* such that holds: *a* part of *b*."
- "Uterus **subClassOf** part-of **only** (Female **or not** Organism)" is to be understood as: "<u>For all</u> uterus instances *a* holds: If there is a *b* of which *a* is a part, then *b* is either female or not an organism."

If we expand on this standard reading, we could extend the universal quantification not only over the instances of the first class mentioned in the assertion, but also over all times. The above sample assertions would then read:

- "For all heart valve instances *a* <u>at all times</u> there is a heart instance *b* such that holds: *a* part of *b*."
- "For all uterus instances *a* holds <u>at all times</u>: If there is a *b* of which *a* is a part, then *b* is either female or not an organism."

This, however, does only permit to express permanent generic relatedness, but not the other two varieties.

SNAP-SPAN. The original suggestion underlying the architecture of the Basic Formal Ontology (BFO; http://www.ifomis.org/bfo) is to have various SNAP-ontologies for various points in time (Grenon 2003; Smith & Grenon 2004). It is, however, not possible to perform this task in OWL: Once the various ontologies are connected with a SPAN ontology and a common namespace is accepted, this approach will lead to contradictions. For example, one SNAP ontology concerning the phase of a butterfly's life in which the butterfly is still a caterpillar would assert "Lepidoptera **subClassOf not** has-part some Wing", while one concerning its adult phase would assert "Lepidoptera **subClassOf** has-part **exactly** 2 Wing", leading to an inconsistency (something cannot have wings and no wings).

Introducing n-ary relations to OWL. There are some strategies to incorporate n-ary relations into OWL (Aranguren et al. 2009; Grewe 2010). These are, however, quite clumsy and seriously impair the processing time of ontologies. Hence, they really are workarounds rather than elegant systematic solutions. For example, one would turn the temporal assertion that butterflies have wings during their adult phase into a series of assertions connecting wings, the adult phase and the butterfly through an intermediate class:

- ButterflyWingRelator **subClassOf**
(relatesSubject **some** Butterfly) **and**
(relatesObject **some** Wing) **and**
(relatesAtTime **some** AdultPhase)
- Butterfly **subClassOf**
subjectOf **some** ButterflyWingRelator

Here the hypothetical class "ButterflyWingRelator" serves as the reification of the original ternary relation and connects its elements.

Temporarily qualified relations. Another option would be to introduce different relation terms for the relations to be distinguished, following the general scheme "R-at-some- time" and "R-at-all-times" (e.g., Smith 2012). According to this strategy we will have at least twice as many relations as one thinks there are: has-part-at-some-time, has-part-at-all-times, has-participant-at-some-time, has-participant-at-all-times.

The main problem of this approach is that the relation names are mere labels for OWL and OWL editors like Protégé – and that they are 'invisible' for the reasoning algorithm. Their semantic content can only be hinted at by way of the subrelation hierarchy that mirrors the implications between the relations. Another drawback of this approach is that it is quite complicated for potential users, as they have to learn and use at least twice as many relations.

4D-Approach. The 4D view (also called 'perdurantism') views objects as four-dimensional space-time 'worms' that can be split up into temporal ‘slices’ (cf. e.g. Welty & Fikes 2006). This would allow us to define as follows:

- x is (at least) a temporary part of y if y if and only if there are time slices x* und y* of x and y, such that x* is part of y*.
- x is a permanent part of y if and only if for all time slices x* of x there exists a time slice y* of y such that x* is part of y*.

This approach does allow a rigorous semantic accounting of the various temporal varieties of relatedness. It is, however, notoriously unclear how to distinguish interesting space-time worms from spatio-temporal junk and it is not clear how to account for time slices: Are they continuants or occurrents? In any case, this method does not square with the 3D approach of both our everyday handling of the world and of biomedical science. We will, therefore, try to replace worms and slices with temporally qualified continuants (TQCs) and describe their place in a 3D ontology.

GFO Presentials. The GFO top-level ontology provides yet another way to account for time-dependent relatedness, which can at least be called “4D inspired”: Instead of continuants that are present as a whole at every point in time of their existence, in GFO there are “presentials”, which are present as a whole at exactly one point in time, thus being analogous to instantaneous time slices. 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 (Herre et al. 2006).

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. Regarding relations of different temporal strength, GFO seems to have adopted an approach where relations are reified as “relators”, which serve as contexts that aggregate the relata as “players” of certain “relational roles” (Loebe 2007). Additionally, GFO accounts for different temporal modes of relatedness precisely by distinguishing between presentials and persistants.

2 TEMPORALLY QUALIFIED CONTINUANTS

2.1 What is a temporally qualified continuant?

In ordinary discourse as well as in formal ontology, we often assume that objects come along with their predefined borders in space and time: When an animal dies, this is the temporal end of an organism. When a caterpillar transforms into a butterfly, this is not the end of an organism, but only the transformation from one state of the organism to another state of the very same organism. The word “butterfly”, that is, does not apply to that organism at any stage of its existence, but only at some very special stage. The word “butterfly” is what is normally referred to as a phase sortal: It refers to a thing in a certain phase of its existence. In a first approximation it could be said that a temporally qualified continuant is the referent of a phase sortal. Examples that fit this descriptions are:

- young Socrates vs old Socrates
- a cell before an intervention vs that cell two days after the intervention
- the juvenile body vs the adult body
- the liver of a child vs the liver of an adult

All these examples are temporal qualifications of independent continuants – of objects or object parts, in the parlance of BFO. We could, however, easily apply the grammatical device of temporal qualification to terms for dependent continuants, too:

- the colour of my skin after contact with the common nettle
- the quantity of Lm11 proteins in the cell eight days after intervention
- the size of the cell eight days after intervention
- the muscle power after two months of training
- the ability to speak two hours after taking drugs
- the function of the sexual hormones in the aging body
- the role of garlic cloves around midnight.

This list of examples neatly displays a sundry of different categories of dependent continuants from BFO.

2.2 Arguments for and against TQCs

To be sure, TQCs seem to be very strange entities, and there are important arguments not to admit them into a serious ontology We briefly sketch the relevant arguments here.

Arguments against TQCs. A strong argument against TQCs can be derived from Occam’s Razor, i.e., the principle of ontological sparsity. Natural language statements that are seemingly about TQCs can be reformulated such that they are statements about non-qualified continuants containing a temporal modality acting on the whole sentence; e.g.: “Old Socrates had grey hair” can be paraphrased as “When he was young, Socrates had grey hair”. Also, old Socrates and young Socrates seem to be the very same person, hence “old Socrates” and “young Socrates” seem to be different labels for the very same entity – and, hence, superfluous.

Arguments in favour of TQCs. On the other side, this ontological commitment has to be compared with the ontological commitments of alternative approaches, which come with their own costs – spatiotemporal worms, temporal slices and so on. We can also argue from the technical necessity of having a technique to express temporary relatedness in OWL ontologies in order to describe, e.g., the morphology of an embryo in the course of its ontogenetic development. It could also be argued that we do distinguish between continuants with different temporal qualifications in ordinary parlance: To claim that young Socrates drank hemlock would not only be odd, but false. This indicates, finally, that young Socrates and old Socrates have incompatible properties and are, thus, not labels of the same entity at all.

2.3 TQCs as Continuants

The basic idea of our suggestion is to take serious the idea that TQCs are continuants. This implies that they can have spatial, but not temporal parts and that they are present 'as a whole' at every time of their existence. When young Socrates was on the Agora at noon, the whole young Socrates was on the Agora at this time.

But how does this new class of TQCs relate to *BFO:Continuant*, i.e., the class of continuants hitherto acknowledged in BFO? Linguistically, TQCs seem to be specially qualified continuants. This would hint at treating *TemporallyQualifiedContinuant* as a subclass of Continuant. The old BFO continuants could, however, also be seen as continuants that are – implicitly – temporally qualified in a very special way, namely with respect to their whole lifespan or history. We would then treat *BFO:Continuant* as a subclass of *TemporallyQualifiedContinuant.*

BFO 2 does already contain the means to talk about the *history* of a material object, which is defined as the totality of processes going on in the spatio-temporal region occupied by the material object. This, in turn, allows us to define the *duration* of an independent continuant as the temporal projection of its history (using the object property *BFO2:projects_onto*).

2.4 Bona fide and fiat boundaries in time

One strategy to make TQCs less offensive is to adopt the distinction between bona fide boundaries and fiat boundaries (Smith 1995, Smith & Varzi 2000; cf. Vogt 2012) to the temporal boundaries of (the history of) material objects. BFO is built around the assumption that some material entities are cut off from their environment by subject-independent physical discontinuities. Other material objects are only cut off from their environment by a cognitive act, i.e., by human fiat: We can distinguish between the upper femur and the lower femur without resorting to a saw.

The same idea can be applied to temporal boundaries: When a vase breaks, this is a definitive temporal end of its existence, as is the death of an organism. Similar thoughts could be applied to the bona fide beginning of an organism's existence (Smith & Broogard 2003). We can then have the maximally temporally extended bona fide continuants that can then be temporally shortened by way of fiat boundaries. These boundaries can be crisp ("Socrates in the first ten years of his life") or vague ("young Socrates"); they can refer to a time measure ("conceptus in the fourth week of pregnancy") or to other properties ("embryo in Carnegie stage 5").

If we expand on this contrast between TQCs and (temporally) bona fide continuants (BFCs), we can state that every TQC is a TQC of some BFC. This gives rise to interesting new relations:

- x hasMax y if and only if y is the BFC of which x is a TQC.

The inverse relation is maxOf; both are transitive. hasMax is functional and a fixpoint relation. These relations can help us to define the equivalence class of all TQCs that are TQCs of the same BFC:

- x and y belong to the same BFC if and only if x hasMax ° maxOf y.

3 PUTTING TQCS TO WORK

3.1 Temporal Variants of Relatedness

We have now all we need to use TQCs to express the various ways of temporal relatedness by means of the restricted expressivity of OWL. In doing so, we assume that all relatedness on the instance level is grounded in some permanent or instantaneous relatedness. X and Y being classes, we can define:

- *Temporary relatedness (class level):* X is temporarily R-related to Y if and only if for every instance x of X there is a TQC x* with x* hasMax x and some TQC y* with y* hasMax some Y such that: x* R y*.
- *Permanent generic relatedness (class level):* X is permanently generically R-related to Y if and only if X **subClassOf** R **some** Y, i.e. if and only if for all TQCs x* with x* hasMax some X there is a TQC y* with y* hasMax some Y such that: x* R y*.
- *Permanent specific relatedness (class level):* X is permanently specifically R-related to Y if and only if
  (1) X subclassOf R some Y and
  (2) X-BFC subclassOf R exactly one Y-BFC.

In the latter specification, properly defining clause (2) requires the introduction of a property chain (for example "R ○ hasMax"). This construction is, however, not permissible in OWL. We are, thus, not able to define permanent specific relatedness due to the restrictions on the use of non-simple object properties in OWL, though augmenting the expressivity by using a rule language such as SWRL provides workarounds for this issue. (Batsakis & Petrakis 2012).

3.2 Transformations

Another interesting relation between TQCs that is of importance for biomedical ontologies is transformation. In a biomedical ontology, something like the following could be stated: *Butterfly transformation_of some Caterpillar*. The Relation Ontology (RO, Smith et al. 2005) defines transformation only on class level (making use of the BFC intuition discussed in the previous section):

- Let C and C' be types of independent continuants. Then C is a transformation_of C' if and only if, for all c and t, if c is an instance of C at t, then there is a time t1 earlier than t, at which c is an instance of C', and there is no time t2 such that c is at t2 both an instance of C and an instance of C'.

However, due to the syntax of OWL (as opposed to OBO), such a definition on class level is not sufficient and we are in need of a definition of transformation on the level of instances. We would want to say, e.g., that old Socrates is a transformation of young Socrates. We can define this as follows:

- x is a transformation of y if and only if (1) x and y are TQCs, (2) x and y are TQCs of the same BFC, and (3) the history of x projects on a later time than the history of y.

4 CONCLUSION

We have introduced the new category of temporally qualified continuants to enhance the expressivity of OWL. With this new category of entities we are able to give strict definitions of temporary and permanent generic relatedness. We can also justify enriching OWL with rules. We are also able to give a definition of transformation on instance level.

Of course, many problems remain. Not the least is the still dubious ontological status of TQCs. Also, we have not discussed the question of whether TQCs need to have a continuous history or whether it could make sense to admit also – even more dubious – non-continuous TQCs ("sleeping Socrates", "contracted mitochondrium").

We could also ask whether the inherence of a TQ-quality in a TQ-substance implies the exact same identity of the duration of these two TQCs or whether it would be sufficient to assume a temporal overlap of the durations. These two options come down to distinguishing a strong and a weak version of predication, and weak predication could be defined with the help of strong predication and TQCs.

ACKNOWLEDGEMENTS

The work presented here is part of a larger co-operative effort to enhance the temporal expressivity of OWL in the course of the development of the OWL-version of BFO 2. The present paper contents itself with the more philosophical aspects of the category of TQCs. We do, however, owe much to discussions with members of this group and to discussions of a related paper on a workshop on time at the Saar University in Saarbrücken. Many thanks are due to Stefan Schulz for written comments on a previous version of this paper, as well as to the reviewers for ODLS.

REFERENCES

Aranguren M et al. (2009), Nary Relationship. *Ontology Design Pattern Public Catalog*, http://www.gong.manchester.ac.uk/odp/html/Nary_Relationship.html.

Batsakis S, Petrakis E (2012), Imposing Restrictions over Temporal Properties in OWL: A Rule-Based Approach. In: Bitakis A, Giurca A, editors. *Rules on the Web: Research and Applications. Proceedings of RuleML 2012*. Berlin et al.: Springer. pp. 240–247.

Grenon, P (2003). BFO in a Nutshell: A Bi-categorical Axiomatization of BFO and Comparison with DOLCE. *IFOMIS Report*, Leipzig.

Grewe N (2010), A generic reification strategy for n-ary relations in DL. In Herre H et al. (ed), *2nd Workshop of Ontologies in Biomedicine and Life Sciences (OBML), Mannheim, 9.-10.9. 2010*, pp. N1-N5.

Herre H et al. (2006) *General Formal Ontology (GFO): A Foundational Ontology Integrating Objects and Processes. Part I:Basic Principles.* Leipzig.

Loebe F (2007) *Abstract vs. social roles — towards a general theoretical account of roles.* Applied Ontology, 2, 127–158.

Motik B, Patel-Schneider P, Parsia B (2012), OWL 2 Web Ontology Language Structural Specification and Functional-Style Syntax. *W3C Recommandation*, http://www.w3.org/TR/2012/REC-owl2-syntax-20121211/.

Smith B (1995), On Drawing Lines on a Map. In: Frank AU, Kuhn W, Mark DM, editors. *Spatial Information Theory: Proceedings in COSIT '95*. Berlin/Heidelberg/Vienna/New York/London/Tokyo: Springer. pp. 475–484.

Smith B et al. (2005), *Relations in biomedical ontologies.* Genome Biology 6(5): R46.

Smith B et al. (2012), *BFO 2, Graz release.* http://purl.obolibrary.org/obo/bfo/2012-07-20/Reference.

Smith B, Brogaard B (2003), Sixteen Days. *Journal of Medicine and Philosophy* 28(1): 45-78.

Smith B, Grenon P (2004), The Cornucopia of Formal-Ontological Relations. *Dialectica* 58(3): 279-296.

Smith B, Varzi AC (2000) Fiat and Bona Fide Boundaries. *Philosophy and Phenomenological Research* 60(2): 401–420.

Vogt L, Grobe P, Quast B, Bartolomaeus T (2012), Fiat or Bona Fide Boundary – A Matter of Granular Perspective. *PLoS ONE* 7(12): e48603. doi:10.1371/journal.pone.0048603.

Welty F, Fikes R (2006), A Reusable Ontology for Fluents in OWL. In: Bennett B, Fellbaum C, editors. *Proceedings of FOIS-2006*, IOS Press, Amsterdam, pp. 226–236.

Wiggins D (1980), Sameness and Substance, Harvard University Press, Cambridge MA.

van Inwagen P (2001), Temporal parts and identity across time. In: *Ontology, Identity and Modality: Essays in Metaphysics*, Cambridge University Press, Cambridge, 122–143.