Patterns for representing time-dependent content in OWL 2 ontologies

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Abstract

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Background: OWL is a popular ontology development language which is supported by a wide range of tools such as editors and reasoners. It is increasingly being adopted by large scale biomedical ontologies such as the Gene Ontology and ChEBI. A limitation of OWL is that it only allows for the expression of binary relationships (object properties). In the biomedical domain, much of the knowledge that is represented in ontologies is linked to time in some fashion. For example, different developmental stages of an organism have different anatomical properties. Representing this information accurately often requires the use of ternary relations (i.e. with an additional parameter), not supported in OWL.

Results: In this paper we present two patterns that address this limitation, emphviz. TR (temporalized relations), which embeds temporalization into OWL object properties, and TQC (temporally qualified continuants), which assumes all continuant instances to be referred to in the context of a time point or interval. A series of 23 modelling examples was created, each of which represented a different type of modelling problems. Each of them was challenged by one formally expressed competency question. A comparison to a manually created reference standard yielded 16 of 23 concordances for TQC and 8 of 23 for TR.

Conclusions: We found the TQC approach more powerful for addressing modelling problems and getting the correct entailments. TR offers a more compact representation but does not allow for explicit time reference for A-Box entities. Interaction with user communities and scaling experiments will be necessary to reach a decision about which should be the appropriate approach to be followed for an OWL version of BFO.

Keywords: biomedical ontology, time, temporal reasoning, OWL, BFO

Background

bfo-owl-time-introduction

This paper addresses a challenge that has arisen in the context of the Open Biomedical Ontologies (OBO) Foundry [1] community, in particular in relation to the implementation of the Basic Formal Ontology (BFO, [2]) version 2, which uses the Web Ontology Language (OWL, [3]). However, the problem is of general interest to the ontology community as a whole, because it exposes and addresses a general weakness of ontology artefacts that use OWL and represent time-related aspects of their domain. Insofar the problem is not restricted to the life science context, and it seems relevant to virtually all domains, in which objects change over time, or are related with each other dependent on temporal contexts.

According to BFO and other foundational ontologies, a useful upper-level distinction is between those entities that exist in full at all times at which they exist (continuants), and those that unfold in time (occurrents). This is a distinction according to temporal mode of existence. Temporal information is also relevant when specifying the relationships between continuant entities, particularly – as for most of the life sciences – where continuants such as organisms and their parts, molecules, shapes, and disorders not only persist, but also continuously change over time. 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.

The Relation Ontology (RO, [4]) proposed patterns for the definition of biological relations to be used throughout bio-ontologies such as the Gene Ontology [5], ChEBI [6] and various anatomy ontologies [7]. The relations proposed include **part_of**, **has_part**, **located_in**, **participates_in**, and **instance_of**. The Relation Ontology specifies exactly how relations at the class level were to be interpreted with regard to time.

That is, in order to capture the statement that every red blood cell has some oxygen molecule located in it, the class-level relation statement *RedBloodCell* **location_of** *OxygenMolecule* (i.e. the red blood cell is the location for the oxygen molecule) should be interpreted as the following first-order logic (FOL) statement:

$$\forall x \forall t : \mathbf{instance\_of}(x, \mathit{RedBloodCell}, t) \rightarrow \exists y : \mathbf{instance\_of}(y, \mathit{OxygenMolecule}, t) \wedge \mathbf{located\_in}(y, x, t) \tag{1}$$

This equation says that at all times that a red blood cell exists, there exists some oxygen molecule (importantly, not necessarily the same one at different times) that is located in the red blood cell *at that time*. Note that instantiation of continuants such as red blood cells and oxygen molecules is also time-indexed in this pattern.

Most of the RO relations were subsequently merged into the BFO during the redesign project, such that BFO, in its second version, now provides definitions for foundational relations like parthood, participation, instantiation, among others. The BFO reference specification follows the RO pattern, allocating a time index to every relation in which a continuant is one of the relata.

The challenge is that, as can be seen in the above formula, relational expressions with a time index are *ternary*, that is, they take three parameters, *viz.* the two relata (which are particulars), and the time index. However, all current variants of the OWL language, for reasons of implementation and reasoning efficiency, allows only *binary* relations. Thus, when relations such as **part_of** are used in class level axioms in practical OWL implementations the time index is lost, which can have surprising reasoning consequences.

The relation between OBO and OWL should be elucidated in more detail

The objective of this paper is the presentation and discussion of OWL design patterns that partly mitigate this limitation. It is organised as follows:

Revise

In the remainder of this Background, we give an overview of the OWL language and BFO ontology into which our proposal will be embedded, and outline our examples and competency questions. Thereafter, we survey the existing approaches to the representation of time-dependent information in we propose and discuss different design patterns and evaluate them against the given examples in the context of their completeness, user friendliness, and performance profile for common reasoning tasks. The concluding section presents our recommendations for the community.

BFO

Basic Formal Ontology (BFO) is an upper level ontology designed to serve as a foundation from which domain ontologies can be built [2]. The use of shared upper level classes and relations mitigates problems that arise when several domain ontologies are used together. For example, the root structure of two ontologies might partially overlap, without explicit mappings clarifying the intended interrelationships (e.g. having classes such as 'process' and 'event'; 'object' and 'thing'). Or the ontologies may make use of similarly named relations without clarifying whether the relations are intended to mean the same thing (e.g., **has_location**, **located_in**, **included_in**,...). They may further re-implement or redefine classes that are defined differently elsewhere.

BFO offers a small set of foundational classes, together with descriptive axioms, most of which make use of a set of foundational relations intended to be used in multiple ontologies. Both classes and relations are domain-independent, although it is clearly stated that BFO's focus is on the representation of natural and applied sciences, with biology and medicine as their most important representatives. Thus, domain-specific relations such as **is_tautomer_of** (a chemical relation used in ChEBI) or **is_about** (in the information artifact ontology) are out of scope for BFO itself, but they should be covered by domain ontologies below BFO, defined according to the RO recommendations.

The uppermost partition in the BFO class hierarchy reflects temporal mode of existence: *continuants* are entities that (1) exist in full at any time that they exists at all, and (2) continue to exist self-identically for as long as they exist; *occurrents* are entities that unfold over a period of time and thus have temporal parts. For example, you are a continuant, while your life is an occurrent. A cell is a continuant, while the process of cell division is an occurrent.

BFO is, primarily, seen as an ontology of types (universals) rather than particulars (individuals). Types extend to general classes of particulars which share important features. For example, the authors of this article are particulars that instantiate the type *Human Being*; a red blood cell in the aorta of the first author and a hepatocyte in the liver of the last author are both particulars that instantiate the type *Cell*. OWL ontologies are, however, ontologies of particulars and their classes. Types and classes look, *prima facie*, isomorphic, and in practice they are often used as synonyms. However, there are subtle differences: classes can be straightforwardly defined via extensions of types: The class A_{class} is defined as the cross-temporal aggregation of all entities that instatiate the type A_{type}. However, classes can also be defined using logical operations such as negation, resulting in classes like *Non-human-animal*, which cannot seen as the extensions of a single type.

In BFO, the realms of types and individuals (or classes and their members) are strictly disjoint: no individual can be instantiated, and no class can be a member of another class. The relation **instance_of** links individuals to their types. A single instance may instantiate many different types (or analogously, be member of many different classes).

In the remainder of this paper we will simplify our model to classes (independently of whether they are extensions of types) and individuals (which are members of classes).

Fig. 1 shows the class and relation hierarchy of BFO 2.

Whereas BFO 1.x was restricted to a tree of mutually disjoint classes, BFO 2.0 now offers an extensive set of relations. Most of these relations relate individuals, not classes or types, which means that when used in class-level axioms, they are subject to an appropriate quantification. Axioms in BFO2 are mainly of the type domain and range restriction, i.e. they restrict the domain of the relation **inheres_in** to specifically dependent continuants, or the range of the relation **participant_of** to processes.

Web Ontology Language (OWL)

OWL (Web Ontology Language) is a family of ontology development languages, which were developed in the context of the Semantic Web, standardised by the the W3C, and which are supported by a wide range of tools including ontology editors such as Protégé and automated reasoners. OWL version 2 is the current one [3], proposing several language profiles of different expressiveness. All but the profile called OWL full are based on Description Logics (DL), a family of representation formalisms designed to build large scale ontologies [8], all of which are decidable fragments of first-order logics. Thes allows classes and relations to be organized in hierarchies, and allows constraining axioms on classes to be formalized. Optionally, assertions about individuals can also be captured.

OWL is increasingly being used in bio-ontologies such as the GO and ChEBI, and this in turn has been driving further biological applications. For example, aspects of OWL expressivity in ChEBI axioms has recently been used to implement an enhanced measure for class-class similarity [9].

As discussed, proper representation of temporal quantification requires the use of ternary relations, with time as their third argument. While there has been work on expressive description logics which might underlie future OWL extensions that try to transcend this limitation [10] and also on description logics that explicitly account for temporality (e.g. [11]), there is as yet no strong push towards standardisation of those formalisms, and tools suitable for end users are not readily available. For the remainder of this paper, therefore, we will work within the expressivity of the core DL profile of OWL 2 which is specified in [12].

The semantics of OWL follows the principles of set theory. OWL object properties are binary predicates between OWL individuals. Well-formed class-level expression therefore require quantifiers when including object properties, such as $\forall$ (`only`) or $\exists$ (`some`).

For instance, the class expression **continuant_part_of** `some` *Cell* specifies the class that contains all individual things that are necessarily part of at least one member of the class *Cell*. The main axiom types available in OWL ontologies are `rdfs : subClassOf`, which allow the construction of class subsumption hierarchies, `owl : equivalentClass`, with which class logical equivalences can be captured, and `rdf : Type`, with which individuals can be assigned to the classes they are members of. For example, *CellMembrane* `subClassOf` **continuant_part_of** `some` *Cell* means that every member of the class *CellMembrane* is part of at least one member of the class *Cell*. The big advantage of OWL ontologies is their formal rigor, their well-studied computational behaviour, their rather intuitive syntax (compared to first-order logics), the presence of editing tools like Protégé, and their support by DL reasoners like HermiT and Fact++, which perform reasoning tasks like consistency and satisfiability checking.

Representing Time

The underspecification of time representations in OWL axioms

Both the OBO axiom

$$\textit{CellMembrane}\ \mathbf{continuant\_part\_of}\ \textit{Cell} \tag{2}$$

and the OWL axiom (often considered equivalent)

$$\textit{CellMembrane}\ \texttt{subClassOf}\ \mathbf{continuant\_part\_of}\ \texttt{some}\ \textit{Cell} \tag{3}$$

do not exhibit any explicit commitment with regard to time. This is not a side aspect, because it makes a difference whether, e.g., a cell membrane is *always* part of some cell or only *at some time*. The lack of temporal definition of OWL statements is especially unsatisfactory when it comes to transitive properties like **continuant_part_of** or **located_in**, where the suppression of the temporal factor can produce plainly wrong entailments, especially at the level of individuals, such as in the following example:

$$\begin{gathered}\mathbf{located\_in(Thrombus\#39874, Heart\#431234)}\\ \mathbf{located\_in(Heart\#431234, Patient\#900812)}\end{gathered} \tag{4}$$

Assuming that the thrombus was no longer in the heart when it was transplanted to Patient#115678, then the entailment

$$\textbf{located\_in}(\textbf{Thrombus\#39874}, \textbf{Patient\#115678}) \tag{5}$$

which follows from the transitivity property of the relation **located_in**, is obviously wrong.

This has a far-reaching consequence: by default, OWL statements of this form are temporally ambiguous in a way that may entail unintended reasoning consequences when domain ontologies are used with real data. (A lack of an explicit treatment of temporal context has previously been implicated in an assessment of the quality of existential restrictions in OBO Foundry ontologies [13].)

Strengths of Relatedness

We will propose a distinction between different temporal *strengths* of relatedness. Before, however, we need to further characterise the ontological status of time, as referred to by the symbol t in our further deliberations. We refrain from a distinction between time intervals and time points, as the latter can be approximated by infinitesimally small intervals. We restrict ourselves to those ternary relations $\mathbf{rel^t}$ for which it can be assumed that whenever they hold for a time interval, they also hold for any of its subintervals, including time points. E.g., if a car is located in a garage during a whole day, it is located therein at any moment or time interval within this day. If a patient's cholesterol level is elevated during a whole year, it is elevated at any shorter amount of time during this year.

Formally:

$$\forall a, b, t, t' : \ \mathbf{rel^t}(a, b, t) \wedge \mathbf{within}(t', t) \rightarrow \mathbf{rel^t}(a, b, t') \tag{6}$$

Some Time Relatedness (STR)

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.

Formally:

$$\begin{aligned} \mathit{TemporarilyRelated}(A, B) =_{def} \forall a, t : \ & \mathbf{inst^t}(A, a, t) \\ & \rightarrow \exists b, t' : \ (\mathbf{inst^t}(B, b, t') \wedge \mathbf{rel^t}(a, b, t') \wedge \mathbf{within}(t', t)) \end{aligned} \tag{7}$$

Permanent Generic Relatedness (PGR)

Informally: for all instances a 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:

(a) all cells have a water molecule as part at all times, but not always the same water molecule.

(b) every bacteria colony has some bacteria as parts at all times, but not always the same bacteria.

$$\begin{aligned} \mathit{PermanentlyGenericallyRelated}(A,B) =_{def} \forall a,t:\ & \mathbf{inst^t}(A,a,t) \\ & \rightarrow \exists b:\ (\mathbf{inst^t}(B,b,t) \wedge \mathbf{rel^t}(a,b,t)) \end{aligned} \tag{8}$$

This case is the standard interpretation of OBO binary class-level relations such as in formula (2), according to [4].

Permanent Specific Relatedness (PSR)

Informally, for all instances a 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) a human being has a brain as part at all times, and it is necessarily the same brain.

(b) a radioactively marked molecule of DNA has the radioactive isotope as part at all times, and it is necessarily the same atom.

$$\begin{aligned} \mathit{PermanentlySpecificallyRelated}(A,B) =_{def}\ & \forall a,t:\ \mathbf{inst^t}(A,a,t) \\ & \rightarrow \exists b:\ \big(\mathbf{inst^t}(B,b,t) \wedge \mathbf{rel^t}(a,b,t)) \\ & \wedge \forall t':(\mathbf{inst^t}(A,a,t') \rightarrow (\mathbf{rel^t}(a,b,t') \wedge \mathbf{inst^t}(B,b,t'))\big) \end{aligned} \tag{9}$$

Methods

Overview

The methodology we pursue in this work serves one major goal, *viz.* to find an optimal way to represent time-related aspects in OWL ontologies. Two competing modeling approaches are introduced and discussed, *Temporalized Relations* (TR) and *Temporally Qualified Continuants* (TQC). Whereas TR integrates time aspects into the definition of OWL object properties, TQC considers all instantiations of continuant classes as temporal slices of continuants. The approach pursued in this paper can be summarized as follows:

- Formulation of time-sensitive examples and competency questions, which represent typical representational tasks and reasoning requirements.
- Formalization of the TR approach.
- Formalization of the TQC approach.
- Representation of examples by both TR and TQC.
- Evaluation by competency questions.

Examples and Competency Questions

The following Examples (EX) and competency questions (CQ) will be used for a comparison of the two representational approaches. For each temporal mode of existence (STR, PGR, PSR) examples are created according to the following criteria: class-level (c), individual-level (i) mereologic (m+), non-mereologic (m-), participation (p), with quantification over the participant (p1) and over the process (p2). In addition we will have a class-level and an individual-level examples for a non-rigid class.

- STR_cm+: Every tooth is part of an organism at some time. Challenged by:
  "tooth for which there is a time it is not part of any organism ": satisfiable

- STR_cm-: Every apple is green at some time
  Challenged by:
  "apple that is only red at some time": satisfiable
- STR_cp1: Every vertebrate participates in some birth process at some time
  Challenged by:
  "Vertebrate that at some time does not participate in a birth process": satisfiable
- STR_cp2: Every fecundation has some spermatozoon as participant at some time
  Challenged by:
  "Fecundation event for which there is never any spermatozoon that participates": unsatisfiable

- STR_im+: "The blood specimen bs430912 is in the lab lab996 during the whole time interval 2013-10-20."

Challenged by:

"The blood specimen bs430912 is in the lab lab100 during the whole time interval 2013-10-20. The labs do not share any facilities " → unsatisfiable

- STR_im-: "Joe‘s left ankle is swollen during the whole time interval 2013-10-20"

  Challenged by: "There is a time within the interval 2013-10-20 in which his ankle is not swollen " → unsatisfiable

- STR_ip: "Mary participated in the process of Mary‘s birth"

  Challenged by:

  "There is a time in which Mary is not a participant in any birth process" → satisfiable

- PGR_cm+: "Every red blood cell always includes some oxygen molecule" Challenged by: "There are red blood cells without oxygen molecules" → unsatisfiable

- PGR_cm-: "Every electronic health record is always on some computer storage"

  Challenged by:

  "There are electronic health records that are not on a computer storage" → unsatisfiable

- PGR_cp1: "Every organism always participates in some ecologic process"

  Challenged by:

  "There are organisms that do not participate in any ecologic process at some time" → unsatisfiable

- PGR_cp2: "Every breathing process has always some volume of air as participant"

  Challenged by:

  "There are parts of breathing processes in which no air volume participates" → unsatisfiable

- PGR_im+: "Mary‘s blood always has as part some blood cell " Challenged by: "There is a time in which Mary‘s blood is devoid of blood cells" → unsatisfiable

- PGR_im-: "Joe‘s electronic health record always resides on some electronic storage medium"

  Challenged by:

  "There is a time in which Joe‘s electronic health record is on hard disk A and another time in which it is only on a different storage" → satisfiable

- PGR_ip: “Joe‘s breathing process has always some volume of air as participant”

  Challenged by:

  “Joe‘s breathing process is without air at some time” → unsatisfiable

- PSR_cm+: “Every human has a brain and it is always the same brain ”

  Challenged by:

  “There is a time in which Joe does not have his first brain” → unsatisfiable

- PSR_cm-: “Every mammal has the same biological sex during its life”

  Challenged by:

  “A mammal that is male at some time and female at some other time” → unsatisfiable

- PSR_cp1: “Every organism always participates in its life, and it is always the same”

  Challenged by:

  “Joe participates in two different lifes” → unsatisfiable

- PSR_cp2: “Every biological life always has some organism as participant, and it is always the same”

  Challenged by:

  “A life that has for some time a human as participant and for some other time another organism as participant” → unsatisfiable

- PSR_im+: “Mary has ‘Mary‘s brain’ as a proper part during her lifetime”

  Challenged by:

  “There is a time in which Mary has no brain” → unsatisfiable

- PSR_im-: “Tibbles, a male cat, has the same sex during his life”

  Challenged by:

  “Tibbles is female at some time during his life” → unsatisfiable

- PSR_ip: “Joe participates in his life and not in any other life”

  Challenged by:

  “Joe participates in a human life and part of his life is a cat life” → unsatisfiable

- NR_t: “Every fetus is an embryo at some time. Nothing can be both an embryo and a fetus at the same time”

  Challenged by:

  “There are fetuses that were never embryos” → unsatisfiable

- NR_i: “John was a medical student from 2001-10-01 to 2007-06-30. Every person who is a medical student was a high school student at some time”

  Challenged by:

  “John was never a high school student” → unsatisfiable

Formalization of both TR and TQR

Based on the BFO 2 technical specification [14] both approaches are expressed in first order logics (FOL). FOL expressions are then transformed in a way that essentially preserves the semantics but is fully based in binary relations. From this formalism, corresponding OWL axioms can be derived.

OWL Implementation and evaluation methods

The TR approach has already been implemented as an OWL ontology. On this basis we develop the TQR ontology by removing all TR-specific relations and add the additional content required for the TQC solution, using Protégé 4.3. These OWL files are then imported into the specific ontologies that implement the examples. We will then assess the examples against competency questions formulated as DL queries. For each example and either ontology (TR vs. TQC) we investigate whether (i) the modelling approach captures the intended semantic, (ii) whether it provides a correct answer to the related competency question, (iii) whether the solution is user-friendly, and (iv), whether it shows a good computational performance.

Proposed Design Patterns

Temporalized Relations (TR)

Of the three patterns *some time relatedness* (STR), *permanent generic relatedness* (PGR), and *permanent specific relatedness* (PSR), STR and PSR have in common that they can be asserted between individuals: a token a can be temporarily related to a token b, e.g. a specific leaf is temporarily part of a specific plant, or a specific human, e.g. Barack Obama, is temporarily located at a specific place, e.g. in his plane Air Force One.

In a similar way, two individuals can be permanently related, such as, e.g., your body mass is permanently inherent in your body, or the planet Earth is permanently part of our solar system.

This allows, in both cases to hide the time argument within a so-called temporalized relation. The STR pattern is introduced as follows:

$$\mathbf{rel\_at\_some\_time^b}(a,b) =_{def} \exists t : \mathbf{rel^t}(a,b,t) \tag{10}$$

This relation can be used in first-order logics axioms such as the individual-level axiom

$$\mathbf{located\_in\_at\_some\_time^b}\ (\mathrm{BarackObama}, \mathrm{AirForceOne}) \tag{11}$$

or in the class-level axiom

$$\forall a:\ \mathbf{inst^b}(\mathit{Leaf}, a) \rightarrow \exists b:\ \mathbf{inst^b}(\mathit{Tree}, b) \wedge \mathbf{part\_of\_at\_some\_time^b}(a,b) \tag{12}$$

with the binary instantiation relation $\mathbf{inst^b}$:

$$\mathbf{inst^b}(A,a) =_{def} \forall t : \mathbf{inst^t}(A,a,t) \tag{13}$$

Analogously, the PSR pattern is introduced as follows:

$$\mathbf{rel\_at\_all\_times^b}(a,b) =_{def} \forall t:\ (\mathbf{exists\_at^b}(a,t)\ \rightarrow\ \mathbf{exists\_at^b}(b,t)\ \wedge\ \mathbf{rel^t}(a,b,t)) \tag{14}$$

This relation can be used in an FOL axiom such as individual-level axiom

$$\mathbf{located\_in\_at\_all\_times^b}\ (\mathrm{Earth}, \mathrm{Solar\_System}) \tag{15}$$

or in the class-level axiom

$$\forall a:\ \mathbf{inst^b}(\mathit{Vertebrate}, a) \rightarrow \exists b:\ \mathbf{inst^b}(\mathit{Spine}, b) \wedge \mathbf{has\_part\_at\_all\_times^b}(a,b) \tag{16}$$

There are several properties that have to be considered for the practical use of temporalized relations. In case a ternary relation is transitive, e.g.

$$\mathbf{rel^t}(a,b,t)\ \wedge\ \mathbf{rel^t}(b,c,t) \rightarrow\ \mathbf{rel^t}(a,c,t) \tag{17}$$

the derived binary STR relation is not, because the implied time argument (cf. Formula 10) is not necessarily identical for the conjoints in a transitive chain. If Obama is in Air Force One at some time, and Air Force One is in Oklahoma City Air Logistics Complex (OC-ALC) at some time, this does not imply that Obama was ever at OC-ALC. Yet there is no problem with inverse STR relations:

$$\mathbf{rel^t}(a,b,t) \ = \ \mathbf{inv\_rel^t}(b,a,t) \tag{18}$$

trivially entails

$$\mathbf{rel^b}(a,b) \ = \ \mathbf{inv\_rel^b}(b,a) \tag{19}$$

If Obama is contained in Air Force One at some time, them Air Force One is the container of Obama at some time.

This is different with PSR. Here, it can be shown that transitivity is maintained: As the relation holds, according to Formula (14) for all times in which the first argument exists, this is also the case for the second argument which becomes the first one in a transitivity chain. However, we cannot assume that the inverse relation of a ternary relation carries over to the binary PSR relation. According to Formula (14), the scope of the quantification over time is only the first argument. It entails the existence of the second argument for the time of the existence of the first one, which, however, does not preclude that the second one outlives the first one. If we say that a certain vertebrate organism always has a spine, this does not preclude that the spine may still exist centuries after the animal's death. This means that the inverse of $\mathbf{has\_continuant\_part\_at\_some\_time^b}$ is not $\mathbf{part\_of\_continuant\_at\_some\_time^b}$, but something like $\mathbf{part\_of\_continuant\_at\_some\_time\_at\_which\_the\_whole\_exists^b}$.

So far we have not considered the PGR case. Being the standard interpretation of class level relations in OBO-RO [4] it has influenced the development of biomedical ontologies for nearly a decade. On closer scrutiny, there is some evidence that many instances of OBO relation assertions would rather correspond to STR, such as in the Foundational Model of Anatomy under real-world conditions: every human heart was part of some human organism, but after the death of the organism it may still continue to exist (in preparation, e.g., for transplantation). Every human may have had teeth, but toothless humans are still humans and teeth can outlive their bearers. In other cases, PGR may be interpreted as PSR, especially in the case of dependent continuants: the redness of a red blood cell always inheres in it. Or the surface of your body cannot jump to a different body. Nevertheless there are enough cases in which PGR is the only acceptable interpretation, especially if we consider PSR as a specialization of PGR.

A major drawback for the temporalized relations approach here is the fact that PGR cannot be expressed by a relation between individual entities. For instance, the statement "every cell nucleus is part of some cell at all times" does not mean that a certain cell nucleus is part of a certain cell. It may become part of a different cell if the original cell fuses with another one and thus becomes a different individual. It is therefore not possible to assert PGR at the level of individuals. Therefore, the OBO "standard case" cannot be directly expressed using a temporalized relation.

However, there is a way to use temporalized relations to represent at least part of the knowledge for which PGR would be the most correct temporal strength.

The reasoning is the following: If we want to express that the classes A and B are related by a permanent generic relationship, such as A obo:*located_in* B, we may resort to *histories*, which are occurrents and can therefore be related by binary relations. According to BFO 2, a history is a complete process that is the sum of the totality of processes taking place in the spatiotemporal region occupied by a material entity or site. Thus, the history of a continuant c can be seen as a four-dimentional spacetime "worm" with a temporal extension that equals the timespan t during which c exists and a three-dimensional spatial extension indexed by each point $t_i \in t$.

Histories can be related by occurrent parthood relations, such as every phase (temporal part) of the history of a cell nucleus is part of the history of some cell (not necessarily of the same cell).

Continuants and their histories are related by the **has_history$^{\mathbf{b}}$** relation (inverse: **history_of$^{\mathbf{b}}$**).

If we want to express that all instances of the class A are always located in some instance of the class B we can express this in FOL in the following way, with **temporal_part_of$^{\mathbf{b}}$** being a relation that holds between two occurrents when the former is a phase or subprocess (a slice or segment) of the latter. **occurrent_part_of$^{\mathbf{b}}$** is the general inclusion relation between two occurrents. Fig. 2 visualizes a situation, in which *viz*that every member of the class A – here depicted by the object a – is always located in some member of B, here represented by the four objects b_1 to b_4. This is expressed by the fact that any temporal part of the history of a is part of the history of some member of B.

Formally:

$$PermanentlyGenericallyLocatedIn(A, B) =_{def}$$

$$\begin{aligned}
&\forall a, h_a, h'_a, t : \mathbf{inst^t}(A, a, t) \wedge \mathbf{inst^b}(Occurrent, h'_a) \\
&\wedge \mathbf{inst^b}(Occurrent, h'_a) \wedge \mathbf{temporal_part_of^b}(h'_a, h_a) \wedge \mathbf{history_of^b}(h_a, a) \rightarrow \\
&\quad \exists b, h_b : \mathbf{inst^t}(B, b, t) \wedge \mathbf{inst^b}(History, j) \wedge \\
&\quad \mathbf{history_of^b}(h_b, b) \wedge \mathbf{occurrent_part_of^b}(h'_a, h_b)
\end{aligned} \tag{20}$$

However, the inclusion of history phases does not allow a distinction between location and parthood [15], so that the relation between a pregnant organism and an embryo or foetus would not be distinguished between the relation between an organism and its brain.

This section should be revised by Alan. Especially the following issues should be discussed: (i) PGR for continuant - continuant relations which are not mereological, such as inherence, concretization, (ii) application to process participants

Temporally Qualified Continuants (TQC)

A *temporal qualification* of a continuant is the result of regarding the continuant in as far as it exists only within a certain portion of time. However, a temporally qualified entity is not an additional entity, it *is* the continuant entity, as *referred to* over a specific period of time, which is within the time the continuant entity exists.

Formally, a temporally qualified continuant (TQC) is a tuple $\langle a, t \rangle$ where a is an instance of a continuant and t is an instance of a temporal region.

TQC's are introduced only in the context of the OWL representation of an ontology. In the FOL representation of the same ontology, the relevant entities are instantiated and related in a time-indexed fashion as per the higher available expressivity. We will give a translation from TQC representation in OWL to FOL representation using ternary relations.

For every continuant there is a temporal qualification that is *maximal* in that it covers the full temporal region over which that continuant exists. The temporal region over which the continuant exists matches the temporal region within which the history of the continuant unfolds. When instances of continuants are created in OWL, without specifying the temporal qualification, it is assumed that the maximal qualification is what is intended.

A separate temporal qualification of the same continuant entity is a different individual in the OWL ontology (related to a different temporal region), but not a different entity in the domain being represented. All of the different temporal qualifications of the same continuant entity share the property of having the same *maximal* temporal qualification.

The following additional binary relations (hence, representable as WOL object properties) are introduced into the ontology to support TQCs:

- **has_max** (inverse **max_of**) relates a random TQC instance to its related instance with the maximal temporal extension (which may be itself)
- **at_some_time** relates a TQC with each other TQC that represents the same continuant. We have chosen this name for a more intuitive understanding of OWL axioms where it is employed.
- The relation **at_some_time** is equivalent to the concatenation **has_max** $\circ$ **max_of**
- **max_of** is a subrelation of **at_some_time**, which is not necessary if **has_max** is represented as a reflexive relation)
- **has_time** relates a TQC with its defining temporal region.

All TQCs must have exactly one temporal region (thus, the **has_time** relation should be considered functional). It follows that instantiation of continuants represented in OWL using the TQC pattern is necessarily time indexed – i.e. a temporal region must always be specified in any instantiation of a TQC. However, for the sake of usability, implementers may wish to assume that when instances of continuants are created in OWL without specifying the qualifying temporal region, the maximal qualification is what is intended.

This can be done with default values relating to the temporal region of the history? Also, how does a TQC relate to a history?

For clarity in the remainder of this discussion, we will use the notation A^{TQ} to denote the class of temporal qualifications of continuants of type A. Note that in the OWL version of an ontology using the TQC design pattern, *only* TQCs (and non-continuant types e.g. occurrents) will be included in the ontology. However, we need to distinguish between A^{TQ} and A for the purpose of showing the translation from OWL to FOL. The following equation relates an instance of A^{TQ} (represented in OWL) to an instance of A (represented in FOL).

$$\forall x: \ (\mathbf{inst^b}(A^{TQ}, x) \rightarrow \exists a, t_0, t_1: \ (\mathbf{inst^t}(A, a, t_0) \wedge \mathbf{equals}(x, a, t_1) \wedge \mathbf{within}(t_1, t_0))) \tag{21}$$

The intended meaning of the predicate **equals** is identity, and **within** specifies inclusion for temporal regions. The relation **has_max** links a TQC to the max TQC for that continuant. That is,

$$\forall x \ \mathbf{inst^b}(A^{TQ}, x) \rightarrow \exists a, t: \ (\mathbf{inst^t}(A, a, t) \wedge \mathbf{has\_max^b}(a, x)) \tag{22}$$

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 proposed representation in OWL.

Some Time Relatedness

We rephrase the definition (7) given above by inserting temporally qualified continuants and derive the form that the relationship takes for temporally qualified continuants and a binary relationship. This is a fairly transparent translation:

$$\begin{aligned} &\mathit{SomeTimeRelated}(A,B) =_{def}\ \forall a,t:\ \mathbf{inst^b}(A,\langle a,t\rangle) \\ &\qquad \to \exists b,t_1:\ (\mathbf{inst^b}(B\langle b,t_1\rangle) \wedge \mathbf{rel^b}(\langle a,t_1\rangle,\langle b,t_1\rangle) \wedge \mathbf{within}(t_1,t)) \end{aligned} \tag{23}$$

We then use the $\mathbf{at\_some\_time^b}$ and $\mathbf{has\_max^b}$ relations and the TQC notation to eliminate the tuples:

$$\begin{aligned} &\mathit{SomeTimeRelated}(A,B) =_{def}\ \forall x:\ \mathbf{inst^b}(A^{TQ},x) \to \exists y,z\ \mathbf{inst^b}(A^{TQ},y)\wedge \\ &\mathbf{inst^b}(B^{TQ},z) \wedge \mathbf{at\_some\_time^b}(y,x) \wedge \mathbf{rel^b}(y,z) \end{aligned} \tag{24}$$

check use of () and ;

This means that the logical form of the expression of 'some time relatedness' is that at least one temporal qualification of A is related to some temporally qualified B instance. However, we need another axiom to constrain $\mathbf{rel^b}$ in the above to ensure that the portions of time are appropriately overlapping, since $\mathbf{rel^t}$ holds at one time only:

$$\forall x,y:\mathbf{rel^b}(x,y) \to \exists t,t_1:\ (\mathbf{has\_time^b}(x,t) \wedge \mathbf{has\_time^b}(y,t_1) \wedge \mathbf{within}(t_1,t)) \tag{25}$$

Now we have derived a binary expression $\mathbf{rel^b}$ we are free to use this in OWL axioms. Temporary relatedness is thus expressed in OWL as follows:

$$A^{TQ}\ \texttt{subClassOf}\ \mathbf{at\_some\_time^b}\ \texttt{some}(\mathbf{rel^b}\ \texttt{some}\ B^{TQ}) \tag{26}$$

Additionally, we ensure that sharing a temporal qualification amounts to being the same continuant:[1]

FIX FOR NEW APPROACH

$$A\ \texttt{hasKey}(\mathbf{has\_max^b}) \tag{27}$$

A Box issues to be discussed separately ?

[1] Implementers should note that OWL 2 only mandates this for *named* individuals.

Permanent Generic Relatedness

Permanent generic relatedness is considered by some to be the most common interpretation of temporally unspecified relations in biology. We have previously defined it in (8), which can now rephrased using the TCQ approach as follows:

$$\forall x:\ \mathbf{inst^b}(A^{TQ}, x) \rightarrow \exists y:\ \mathbf{inst^b}(B^{TQ}, y) \wedge \mathbf{rel^b}(x, y) \tag{28}$$

Informally, this means that, whatever temporal qualification of an instance of A we choose, it will always be **rel**-related to some temporal qualification of type B, but we neither care nor enforce which one.

This is the easiest and most elegant translation case from the FOL perspective. Moving to OWL, the above axiom (28) appears as:

$$A^{TQ}\ \texttt{subClassOf}\ \mathbf{rel^b}\ \texttt{some}\ B^{TQ} \tag{29}$$

The availability and elegance of permanent generic relatedness in this design pattern is noteworthy because it would not be possible in OWL 2 in the absence of temporally qualified continuants, as instantiation of classes and of object property tuples is rigid.

Permanent Specific Relatedness

Permanent specific relatedness cannot elegantly be accommodated within the TQC design pattern.

If we do introduce an explicit object property, could we hope to arrive at implementing something like permanent specific relatedness (9)? Unfortunately, this assumption proves to be too naïve.

It would require an additional axiom to ensure that only TQCs of the same continuant instance are involved for the second relatum. Unfortunately, we cannot provide an accurate translation of this kind of relatedness into OWL 2, though we can achieve the following first order translation in TQC-talk:

This formula seems really wrong

$$\begin{aligned}
&\forall x:\ \mathbf{inst^b}(A^{TQ}, x) \rightarrow \\
&\quad \exists y: \mathbf{inst^b}(B^{TQ}, y) \wedge \mathbf{rel^b}(x, y) \wedge \\
&\qquad \forall x_1, a:\ ((\mathbf{inst^b}(A^{TQ}, x_1) \wedge \mathbf{has_max^b}(a, x) \wedge \mathbf{has_max^b}(a, x_1)) \wedge \\
&\qquad\quad \exists y_1, b:\ (\mathbf{inst^b}(B^{TQ}, y_1) \mathbf{has_max^b}(b, y) \wedge \mathbf{has_max^b}(b, y_1) \wedge \\
&\qquad\quad \mathbf{rel^b}(x_1, y_1)))
\end{aligned} \tag{30}$$

Table 1: Overview of results of competency question. Comparison between TR and TQC. The asterisk marks those examples which could con be fully modelled.
(see separate PDF file)

This would require three variables (x, y, y_1) to be bound at the same time, which is incompatible with any OWL translation.

The following according to Niels' proposal

A possible way of expressing (most of) the notion of 'permanent specific relatedness' is a syntactic variant of the 'some time relatedness' pattern:

$$\begin{aligned} \mathit{PermanentSpecificallyRelated}(A, B) =_{def} \ \forall x : \ \mathbf{inst^b}(A^{TQ}, x) \rightarrow \exists y, z \ \mathbf{inst^b}(A^{TQ}, y) \wedge \\ \mathbf{inst^b}(B^{TQ}, z) \wedge \mathbf{has\_max^b}(y, x) \wedge \mathbf{rel^b}(y, z) \end{aligned} \tag{31}$$

In the same way as in formula **??** we can translate this straightforwardly into OWL axioms. Temporary relatedness is thus expressed in OWL as follows:

$$A^{TQ} \ \texttt{subClassOf} \ \mathbf{has\_max^b} \ \texttt{some}(\mathbf{rel^b} \ \texttt{some} \ B^{TQ}) \tag{32}$$

Results

OWL models

According to the specifications two OWL models for BFO were used. The first one, implementing the TR (temporalized relations) approach, is a minor update to the BFO2OWL "Graz" release (July 2012), with 78 object properties. The second one was newly built following the BFO2 specification and extending the set of object properties only by "**at some time**", "**has max**" and "**spans**", with a total number of 58 object properties.

The results of the OWL implementations of the examples can be inspected in the additional files. Table 1 provides an overview of the results. Each of the 23 examples had been implemented in both TQR and TR. In TR the models for STR_im+, STR_im-, PGR_im-, NR_t and NR_i were underspecified, as the TR implementation does not address specific time intervals.

Of those competency questions for which satisfiability was expected (n= 5), the TR model was satisfiable in one case, whereas the TQC model was satisfiable in all cases.

Of the competency questions for which insatisfiability was expected (n= 18), this could be confirmed by the TR model in seven cases, whereas it was obtained by the TQC model in eleven cases.

In detail the following observations are considered noteworthy for the TR approach:

- As the TR models of some time relatedness do not make their semantics explicit, an important class of modeling patterns are too strong. Generally spoken, if A is "all time related" to B, it is also "some time related". For instance, we want to say that although every anatomical structure is part of an organism at least during some time, there are anatomical structures that exist even severed from the body, e.g. teeth. In TR this produces a contradiction, due to the abovementioned reason, whereas in TQC the statement there are temporal slices (TQCs) in which the parthood predicate does not hold perfectly harmonizes with the statement that it holds with other TQCs.

- As TR does not provide sufficient resources that would allow for stating a relatedness during a certain time, important inferences such as that an object cannot be at a place p' at a given time because it is already at p (which does not share parts with p') cannot be drawn. However, TQR here reaches its limits if the reasoning has to account for different, possibly overlapping time intervals. An example is our example with the swollen ankle. Both approaches fail to demonstrate the contradiction in the statement that the ankle is swollen during a given time period but is not swollen during an interval within that period.

- As a consequence of the previous observation, the representation of phased sortals, here the embryo / fetus example, is incomplete and leads to inconsistencies in case the phased sortal classes are introduced as disjoint. A distinction between (i) c being a member of C_1 at one time and C_2 at a different time, and (ii) c being a member of the intersection of the classes C_1 and C_2 is not possible. find related work, e.g. re Allan's interval calculus and DL

- As generic all time relatedness can only be expressed in TR for mereological relations, we would expect a wrong result in the example with a generically dependent continuant, *viz* the electronic health record. What happens is that in PGR_cm- the TR model produces a correct result, however based on an incomplete premise, *viz.* stating that the data are on a storage device only for some time (which allows for the unintended model that they are not stored anywhere for some time).

- As expected, TR fares better where the specific all time relatedness. The advantage is exemplified in the PSR_cm+ reasoning example, where the (wrong) model in which a human gets a brain transplant

Table 2: Classification times of ontologies in ms

	TR	**TQC**	**TR + examples**	**TQC + examples**
Fact++	217	185	1,008	2,050
HermiT	2,580	1,736	41,801	38,665

is rejected. However, both TR and TQC approaches fail with the example of changing sex in mammals.

Classification times were measured for the DL classifiers Fact++ and HermiT 1.3.8. using an 8 core lenovo Think Pad T530 laptop with 8 GByte memory, cr. 2.

Discussion

In the following, we will provide a survey of existing approaches and discuss them in the light of our models.

Histories in BFO 2

BFO 2, which is currently available as an advanced draft [14], sketches out a more detailed theory of the relationship between continuants and occurrents they participate in. Specifically, BFO 2 makes the assumption that for each material object there exists a special process, the *history* of the object, which encompasses "the totality of processes taking place in the spatiotemporal region occupied by the entity." This means that there is a one to one correspondence between continuants and certain processes, which effectively provides a "bridge" between a 3D and a 4D perspective. No complete formal theory of histories, which have previously been described in [16], is available as of yet.

Conventional Modellers' Strategy for Temporalised Relations in OWL DL

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 Foundational Model of Anatomy (FMA), the object property **has_part** is transitive, and used in axioms such as

$$\textit{Lung}\ \texttt{subClassOf}\ \textbf{has\_part}\ \texttt{some}\ \textit{LobeOfLung} \tag{33}$$

and

$$\textit{LobeOfLung}\ \texttt{subClassOf}\ \textbf{has\_part}\ \texttt{some}\ \textit{BronchiopulmonarySegment} \tag{34}$$

If the underlying interpretation were "part for some time", transitivity of the binary **has_part** could no longer be taken for granted.

It is surprising that it has not been spotted earlier that virtually all OWL ontologies contain axioms on classes of continuants using binary object properties and leave the exact interpretation re time unexplained. In a similar vein RDF encoded triple data abound in which the temporal context is ignored, or, at best, derivable from the context.

To address this mismatch and try to understand it better we sketch here a possible elucidation which consists in a modification of the interpretation function. We here make explicit what seems to be trivial for many OWL DL users, *viz.* that a DL formula is to be interpreted as the set of possible worlds over which the formula holds, which would also include all temporal contexts.

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 hat 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 $\cdot^{\mathcal{I}}$):

$$\forall t:\ \langle a^{\mathcal{I}}, t\rangle \in \Delta^{\mathcal{I}} \rightarrow \langle a^{\mathcal{I}}, t\rangle \in C^{\mathcal{I}} \tag{35}$$

We implicitly assume that Δ contains individual/time-point pairs only for those times at which an individual exists. Notably, this is only sufficient to 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 generic 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 [17] to ease comparison with the specified semantics [12].

Existential quantification ($\mathbf{rel^b}$ `some` B)

$$\begin{aligned}&\text{ObjectSomeValuesFrom}(\mathbf{rel^b}, B)^{\mathcal{I}} =_{def}\\ &\qquad\{\langle a^{\mathcal{I}}, t\rangle \in \Delta^{\mathcal{I}} \mid \exists b:\ \langle a^{\mathcal{I}}, b, t\rangle \in \mathbf{rel^t}^{\mathcal{I}} \wedge \langle b, t\rangle \in B^{\mathcal{I}}\}\end{aligned} \tag{36}$$

Table 3: Syntactical representations of (permanent) relatedness expressions

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

Value restriction ($\mathbf{rel^b}$ `only` B)

$$\begin{aligned}&\text{ObjectAllValuesFrom}(\mathbf{rel^b}, B)^{\mathcal{I}} =_{def} \\ &\qquad\qquad \{\langle a^{\mathcal{I}}, t\rangle \in \Delta^{\mathcal{I}} \mid \forall b:\ \langle a^{\mathcal{I}}, b, t\rangle \in \mathbf{rel^t}^{\mathcal{I}} \rightarrow \langle b, t\rangle \in B^{\mathcal{I}}\}\end{aligned} \tag{37}$$

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

$$\text{ObjectPropertyAssertion}(\mathbf{rel^b}, a, b) =_{def}\ \forall t:\ \langle a^{\mathcal{I}}, t\rangle \in \Delta^{\mathcal{I}} \rightarrow \langle a^{\mathcal{I}}, b^{\mathcal{I}}, t\rangle \in \mathbf{rel^t}^{\mathcal{I}} \tag{38}$$

Hence, object property assertions specify permanent relatedness. Disregarding the difference between specific and generic permanent relatedness for the time being, this interpretation of OWL 2 at least successfully mimics the semantics of class level relations intended by the relations ontology (RO, [4]) and allows us to think of the syntactical forms represented in Table 3 as equivalent.

This approach also retains standard transitivity semantics of OWL 2 object properties, so that quantification over time maintains transitivity of the relation in question. This can be shown, e.g. for the transitive relation **has_part**: 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:

$$\frac{A\ \texttt{subClassOf}\ \mathbf{has\_part^b}\ \texttt{some}\ B \qquad B\ \texttt{subClassOf}\ \mathbf{has\_part^b}\ \texttt{some}\ C}{A\ \texttt{subClassOf}\ \mathbf{has\_part^b}\ \texttt{some}\ C}$$

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 still has 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.

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 $C_{\mathbf{rel^t}}$ for each ternary relation $\mathbf{rel^t}$. The relata of $\mathbf{rel^t}$ are then connected to instances of $C_{\mathbf{rel^t}}$ by three new binary relations $\mathbf{R_1^b}$, $\mathbf{R_2^b}$, $\mathbf{R_3^b}$. The instance-level assertion

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

would then be transformed into the following statement:

Changed from list of statements to proper axiom

$$\exists x : C_{\mathbf{rel^t}}(x) \land \mathbf{R_1^b}(x, a) \land \mathbf{R_2^b}(x, b) \land \mathbf{R_3^b}(x, t) \tag{39}$$

Such proposals have, with a varying degree of sophistication, seen quite a bit of dissemination in the ontology engineering community [18], but they suffer from unavoidable drawbacks. Most obviously, they are rather complex. This bears the risk of errors in the ontology engineering process and decreases reasoning efficiency [19]. 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 [20].

unclear how transitive relations can be expressed by this without proliferation of object properties

Welty/Fikes: Fluents

The prototypical approach for dealing with temporally changing information in OWL within a four-dimensionalist framework was provided by [21]. And while the proponents agree that the 4D approach is "clearly not something that immediately appeals to common sense", they also claim that it "gives us another tool to use when solving a practical problem." To this end, they present an ontology that models fluents, i.e. "relations that hold within certain time interval but not in others." This works by considering all entities as four dimensional entities that have temporal parts (time slices), such that the material object property assertions hold (synchronously) between time slices. For example, temporary relatedness could be expressed as in (40).

$$\textit{Leaf}\ \texttt{subClassOf}\ \texttt{inverseOf}(\mathbf{time\_slice\_of^b})\ \texttt{some}\ (\mathbf{has\_part^b}\ \texttt{some}\ (\mathbf{time\_slice\_of^b}\ \texttt{some}\ \textit{Tree})) \tag{40}$$

This is by far one of the most straightforward translations of the four-dimensionalist commitment, but it suffers from considerable verbosity. It gets even worse if permanent relatedness is concerned. In this case, the above expression would have to be amended to include an `inverseOf`(**time_slice_of$^{\mathbf{b}}$**) `only` clause to ensure that all time slices of the entity are appropriately related to a time slice of the other entity.

Zamborlini/Guizzardi: Moments, Relators and Qua-Individuals

The commitment that some relational expressions are in fact better accounted for as proper entities is also prominent in Zamborlini and Guizzardi's treatment of contingent properties [22]. For them, certain "material relations" only hold by virtue of a separate truthmaker, the so called *relator*, which is formed by combining the "qua individuals" that partake in the relation. Qua individuals abstract away certain aspects of an individual so that only that information remains which is relevant for the individuals participation in the relation.

Both kinds of entities are examples of "moments" in their nomenclature, which are said to inhere in individual entities and can thus be compared to dependent continuants or occurrents (respectively) in BFO parlance. But while relators might often be appropriately represented by BFO processes, the admissibility of qua individuals into BFO might be questionable since they can hardly be aligned with BFO's realist commitment (where sheer abstractions could only be regarded as artefacts of a persons though process).

Underneath the level of qua individuals (e.g. "*LeafQuaPartOfTree*") and relators, there is the assumption of an ontology of time slices not unlike the one in [21], such that temporal overlap between the qua individuals related by the relator can be enforced.

Zamborlini and Guizzardi cite as an advantage for this approach that it is capable of representing the persistence of a relationship across multiple time slices without mentioning each explicitly (because the relator is associated with the qua-individual and not its time slice). This is part of a set of requirements suggested for modelling temporally changing information:

1. Avoid duplication of the other time slices if one entity partaking in the relation changes.
2. Provide a consistent ontological interpretation of contingent (non-rigid) instantiation.
3. Avoid repeating persisting properties for each time slice
4. Ensure that immutable properties of an entity cannot be overridden by a time slice.

We believe these points to be a good starting point for the evaluation of any proposal to address the problem of time-dependent relation and should be used to supplement our initial requirements.

Gangemi: Descriptions and Situations

should specify what is meant by situations here

Aldo Gangemi's DnS pattern [23] deserves mention because it treats time-dependence of relations as a special case of perspectivity which can be accounted for by the very heavy-duty reification mechanism of descriptions and situations. In this case, the suggestion is to use the situation pattern in order to associate the relata and their temporal context with a common situation, which is effectively a reified assertion (a proposition). Again, such entities are figments of the mind and can only be admitted into a realist ontology such as BFO as such – rather than being a general way to refer to arbitrary facts.

Notably, though, Gangemi reminds us of the fact that OWL 2's `hasKey` axiom can be used circumvent the problem of possible duplication of instances for the same relational n-tuple: If a situation S

don't understand

were to use the properties **has_timeStamp**$^{\mathbf{b}}$, **has_subject**$^{\mathbf{b}}$, and **has_object**$^{\mathbf{b}}$, the axiom

$$S\ \texttt{hasKey}(\mathbf{has\_timeStamp^b}, \mathbf{has\_subject^b}, \mathbf{has\_object^b}) \tag{41}$$

would ensure that duplicate entities would be coalesced in the model.

Temporal extension to Description Logics

Extensions to description logics to include temporal notions have been proposed by ...

We have not considered these approaches because they are not covered by the OWL specification and do not yet provide mature tools like editors and reasoners.

Performance

The benchmark results show no great differences between TR and TQC, however with quite lower classification times for Fact++ compared with HermiT. If adding examples the decrease in performance is more accentuated for TQC compared to TR, which is explained by the lower number of A-Box axioms in the latter, due to the impossibility of representing specific times.

We also observed that declaring the has_max relation as functional has a negative impact on the Fact++ reasoner, which fails to terminate, while HermiT does terminate. (Check). Setting has_max and max_of to be reflexive causes inconsistencies (explanations hint at an interference with existsAt).

Relevance (or not) to other top-level ontologies

todo[inline, size=]do we need this subsection?

Patterns

From a usability point of view, TR may have an advantage due to the embedding of a complex meaning within relations. While the higher number of relations might complicate navigation in relation hierarchies, the axioms built out of them appear more straightforward. However, this requires that users completely understand the meaning of each relation. This is a challenge especially with the inverse relations, and the unintuitive fact that, e.g. 'has part at all times' is not the inverse of 'part of at all times'.

TQR is the leaner ontology, due to a much more concise set of relations. However, it requires a fundamental understanding of the meaning of TQCs. Syntactically, most axioms look the same as in the modelling strategies that ignore temporal qualification. This might be a advantage for the adaption of existing domain ontologies. The expression of "some time" relatedness requires an additional nesting, using the relation "at_some_time", which connects temporal instances of the same continuant. In particular, four patterns can be distinguished:

- Class-level assertion A valid for a given TQC individual c:

$$\mathbf{c}\ \texttt{Type}\ A \tag{42}$$

- Class-level assertion A valid for all related temporal slices of a given TQC individual c:

$$\mathbf{at\_some\_time}\ \texttt{value}\ \mathbf{c}\ \texttt{subClassOf}\ A \tag{43}$$

- Class-level assertion A valid for at least one temporal slice for each member of a TQC class C:

$$C\ \texttt{subClassOf}\ \mathbf{at\_some\_time}\ \texttt{some}\ A \tag{44}$$

- Class-level assertion A valid for all related temporal slices of all members of a TQC class C:

$$C\ \texttt{subClassOf}\ A \tag{45}$$

Conclusions

In this paper we have addressed an inhering limitation of current OWL dialects, *viz.* their limitation to binary relations, whereas the current version of the Basic Formal Ontology, BFO2, requires ternary relations wherever continuants are involved. The argument is that relations between continuants (such as spatial location) as well as between a continuant and an occurrent (e.g. participation of an object in a process) are time dependent. Therefore, such relationships require time as a third parameter. Up to now, builders of OWL ontologies have tacitly assumed relational expressions in OWL to range over all instants in time. This assumption falls short of expressing relationships that do not hold for all times the relata exists, which entails improper and underspecified expressions both an A-box and a T-Box level.

Two principally different approaches have been introduced, *viz.* TR (temporalized relations), which embeds temporalization into OWL object properties, and TQC (temporally qualified continuants), which assumes all continuant instances to be temporally qualified, i.e. referred to in the context of a time point or interval. Whereas both approaches manage quite well to distinguish between temporary and permanent relatedness, they fundamentally differ in their account of the latter. Here, TQC offers a straightforward solution for what we call generic relatedness, which focuses of the type of the relata rather than on the individual permanence of relationship. In contrast, TR prefers permanent relatedness and only offers an indirect approach to represent generic relatedness, which is furthermore limited to the spatial inclusion relation (expressed as the spatiotemporal inclusion relation between the *histories* or the related continuants.

A series of 23 modelling examples was created, each of which represented a different type of modelling problems. Each of them was challenged by one competency question, expressed as DL queries for class-level examples, and A-level expressions in case of individual-level examples. They were tested for satisfiability and compared to the theoretically established reference standard.

As a result, concordance with the reference standard was achieved for 16 of 23 representations using the TQC approach, and 8 of 23 using TR. The lower result for TR is affected by its limited expressiveness regarding time-indexed relationships at an A-box level. Since the reference to time is contained in the (primitive) meaning the object properties, it offers no resource of precisely expressing time-related assertions on the level of individuals. This is possible with TQC. Each A-Box statement in which a continuant is involved is necessarily time indexed. Statements that range about continuants at several time instants require T-Box expressions, as classes of TQCs have to be built. More advanced querying, e.g. involving nested time intervals are not supported. They may require an additional rule language, which, however lies beyond the scope of this paper.

The decision whether to prefer TR or TQC as basis of an OWL version of BFO2, will have to been taken after more case studies and in dialogue with the BFO user community.

Author's contributions in alphabetical order

Niels Grewe produced the first formalization of the TQC approach and described the related work. Chris Mungall participated in the discussion of the TR approach. Janna Hastings contributed to the foundations of the TQC approach and participated in the editing of the final version. Ludger Jansen contriTQC formalizations and the related work. Fabian Neuhaus refined the TQC approach. Alan Ruttenberg formulated the TR approach and implemented the TR version of BFO. Barry Smith is the main author of BFO 2 and contributed to discussions around TR and TQC. Stefan Schulz contributed to the first sketch of TQC, created the used cases and competency questions, the OWL implementations for the TQR scenarios and the examples, performed the experiments and edited the final version.

Acknowledgements

The research by NG, LJ and SS for this paper has been supported by the German Science Foundation (DFG), grant JA1904/2-1, SCHU 2515/1-1 as part of the research project "Good Ontology Design". JH is supported by the European Union under EU-OPENSCREEN. The authors would like to thank Melissa Haendel, David Osumi-Sutherland, Colin Batchelor and ... for helpful discussions.

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Figures

[width=120mm]bfograph.png

Figure 1: Classes and relations in BFO 2.0

[width=120mm]trgraph.png

Figure 2: Permanent generic location as inclusion of histories. The object a (depicted as a spatiotemporal "worm")is always included in some member of the class B, *viz* b_1, b_2, b_3, b_4.

Tables

Big table, encompassing all examples and competency questions. The source of this table is an Excel spreadsheet, from which a PDF file was created

Table 1. Results

examples and competency questions for both TR and TQC approaches. For each example and modelling approach the satisfiability is given: Y = satisfiable and N = not satisfiable. The reasoning example can be inspected in the additional files.

Additional Files

BFO OWL with temporalized relations

This file (bfo_tr.owl) corresponds to “BFO OWL Graz” as released in July 2012. It includes temporalized relations such as “has continuant part at all times”, “inheres in at some time” etc.

BFO OWL with temporally qualified continuants

This file (bfo_tqc.owl)corresponds does not include temporalized relations and strictly follows the relations as provided by the BFO reference guide. All ternary relations are reduced to binary object properties involving temporally qualified continuants (TQCs). For the handling of TQCs additional object properties were added, as described in this paper.

examples for temporalized relations

This file (bfo_tr_uc.owl)contains the examples as described in this paper. It imports bfo_tr.owl.

examples for temporally qualified continuants

This file (bfo_tqc_uc.owl)contains the examples as described in this paper. It imports bfo_tqc.owl.


entity
continuant
'generically dependent continuant'
'independent continuant'
'immaterial entity'
'continuant fiat boundary'
'one-dimensional continuant fiat boundary'
'two-dimensional continuant fiat boundary'
'zero-dimensional continuant fiat boundary'
site
'spatial region'
'one-dimensional spatial region'
'three-dimensional spatial region'
'two-dimensional spatial region'
'zero-dimensional spatial region'
'material entity'
'fiat object'
object
'object aggregate'
'specifically dependent continuant'
quality
'relational quality'
'realizable entity'
disposition
function
role
occurrent
process
history
'process profile'
'process boundary'
'spatiotemporal region'
'temporal region'
'one-dimensional temporal region'
'zero-dimensional temporal region'
'concretized by'
concretizes
'contains process'
'has history'
'during which exists'
'has temporal occupant'
'temporal projection of spatiotemporal'
'exists at'
'occupies temporal region'
'projects onto temporal region'
spans
'generically depends on'
'has generic dependent'
'has material basis'
'has occurrent part'
'has proper occurrent part'
'has proper temporal part'
'has temporal part'
'has proper temporal part'
'has profile'
'has spatial occupant'
'has spatiotemporal occupant'
'has specific dependent'
'bearer of'
'has disposition'
'has function'
'has quality'
'has role'
'has history'
'participates in'
'located in'
'part of continuant'
'location of'
'has continuant part'
'has member part'
'has proper continuant part'
'material basis of'
'occupies spatial region'
'occupies spatiotemporal region'
'occurs in'
'history of'
'part of occurrent'
'proper part of occurrent'
'proper temporal part of'
'temporal part of'
'proper temporal part of'
'process profile of'
'projects onto spatial region'
'realized in'
realizes
'spatial projection of spatiotemporal'
'specifically depends on'
'has participant'
'history of'
'inheres in'
'disposition of'
'function of'
'quality of'
'role of'

Fig. 1

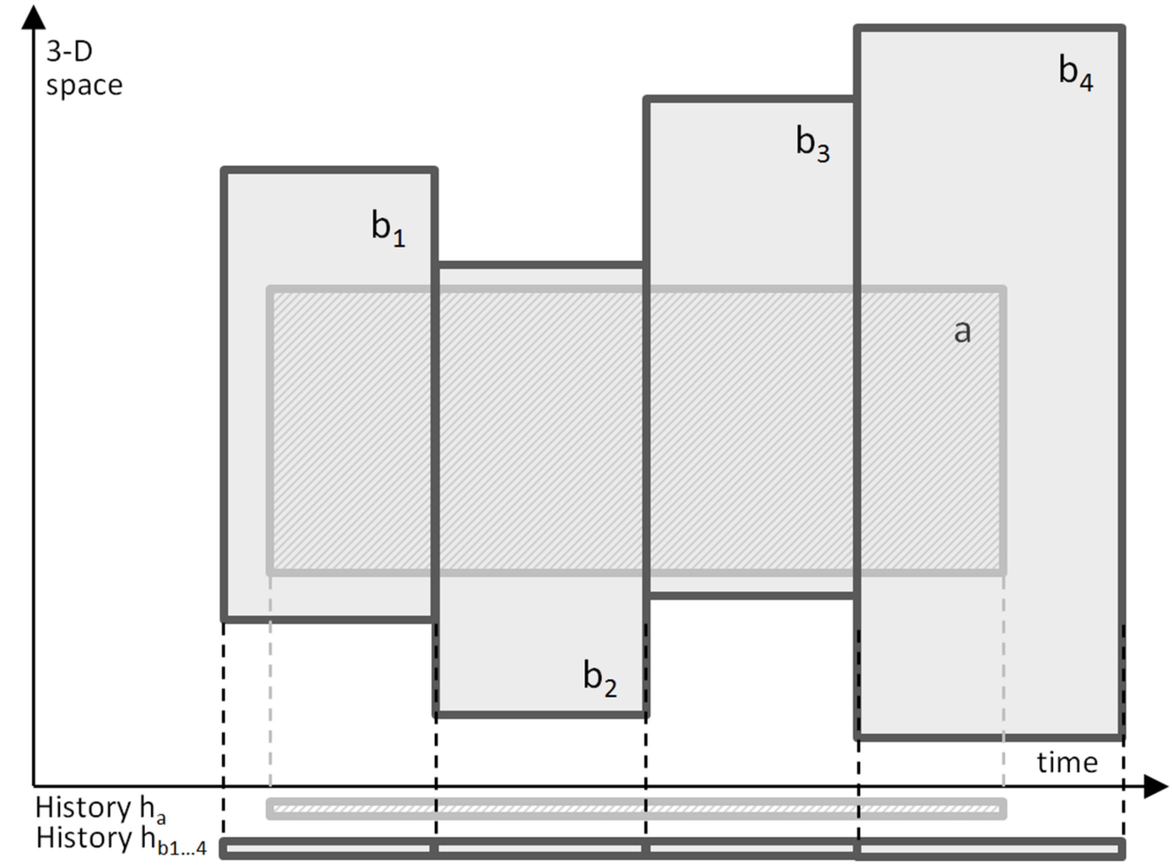

Fig. 2

	Example	Satisfiability (expected)	TR pattern	Satisfiability TR	TQC pattern	Satisfiability TQC
STR_cm+	Every tooth is part of an organism at some time		tooth subclassOf 'part of continuant at some time' some organism		tooth subClassOf 'at some time' some ('part of continuant' some organism)	
	tooth for which there is a time it is not part of any organism	Y	tooth and not 'part of continuant at all times' some organism	N	tooth and 'at some time' some ('part of continuant' only (not organism))	Y
STR_cm-	Every apple is green at some time		apple subClassOf 'has quality at some time' some 'green color'		apple subClassOf 'at some time' some ('has quality' some 'green color')	
	apple that is only red at some time	Y	apple and 'has quality at some time' only ('red color' or not color) and 'has quality at some time' some 'red color'	N	apple and 'at some time' some ('has quality' only ('red color' or not color))	Y
STR_cp1	Every vertebrate participates in some birth process at some time		vertebrate subClassOf 'participates in at some time' some 'birth process'		vertebrate subClassOf 'at some time' some ('participates in' some 'birth process')	
	Vertebrate that at some time does not participate in a birth process	Y	vertebrate and not ('participates in at all times' some 'birth process')	Y	vertebrate and 'at some time' some (not ('participates in' some 'birth process'))	Y
STR_cp2	Every fecundation has some spermatozoon as participant at some time		fecundation subClassOf 'has participant at some time' some spermatozoon		fecundation subClassOf 'has participant' some spermatozoon	
	Fecundation event for which there is never any spermatozoon that participates	N	fecundation and not ('has participant at some time' some spermatozoon)	N	fecundation and not ('has participant' some spermatozoon)	N
STR_im+	The blood specimen bs430912 is in the lab lab996 during the whole time interval 2013-10-20.		bs 430912' 'located in at some times' 'lab 996'	*	'bs 430912 at 2013-10-20' 'located in' 'lab 110 at 2013-10-20'	
	The blood specimen bs430912 is in the lab lab100 during the whole time interval 2013-10-20. The labs do not share any facilities	N	bs 430912 'located in at some times' 'lab 100' 'located in at all times' value 'lab 100' subClassOf not('located in at all times' value 'lab 996')	Y	'bs 430912 at 2013-10-20' 'located in' 'lab 996 at 2013-10-20'	N
STR_im-	Joe`s left ankle is swollen during the whole time interval 2013-10-20		Joe`s left ankle' value 'has quality at some time' some swollen	*	'Joe`s left ankle at 2013-10-20' Type 'has quality' some swollen	
	There is a time within the interval 2013-10-20 in which his ankle is not swollen	N	Joe`s left ankle' value not ('has quality at all times' some swollen)	Y	('has max' value 'Joe`s left ankle max') and spans some ('temporal part of' value 2013-10-20) and not ('has quality' some swollen)	Y
STR_ip	Mary participated in the process of Mary`s birth		Mary 'participates in at some time' 'Mary`s birth'		'Mary max' Type ('at some time' some ('participates in' value 'Mary`s birth'))	
	There is a time in which Mary is not a participant in any birth process	Y	Mary Type not ('participates in at all times' some 'birth process')	N	('has max' value 'Mary max') and not ('participates in' some 'birth process')	Y
PGR_cm+	Every red blood cell always includes some oxygen molecule		history of' some 'red blood cell' subClassOf 'has occurrent part' some ('part of occurrent' some ('history of' some 'oxygen molecule'))		'red blood cell' subClassOf 'location of' some 'oxygen molecule'	
	There are red blood cells without oxygen molecules	N	red blood cell' and 'has continuant part at some time' only (not 'oxygen molecule')	Y	'red blood cell' and (not ('location of' some 'oxygen molecule'))	N
PGR_cm-	Every electronic health record is always on some computer storage		electronic health record' subClassOf 'generically depends on at some time' some 'computer storage'	*	'electronic health record' subClassOf 'generically depends on' some 'computer storage'	
	There are electronic health records that are not on a computer storage	N	electronic health record' and not ('generically depends on at some time' some 'computer storage'	N	'electronic health record' and not ('generically depends on' some 'computer storage')	N
PGR_cp1	Every organism always participates in some ecologic process		organism subClassOf 'participates in at some time' some 'ecologic process'		organism subClassOf 'participates in' some 'ecologic process'	
	There are organisms that do not participate in any ecologic process at some time	N	organism and not ('participates in at all times' some 'ecologic process')	N	organism and not ('participates in' some 'ecologic process')	N
PGR_cp2	Every breathing process has always some volume of air as participant		temporal part of' some 'breathing process' subClassOf 'has occurrent part' some ('part of occurrent' some ('history of' some 'volume of air'))		'temporal part of' some 'breathing process' SubClassOf 'has participant' some 'volume of air'	
	There are parts of breathing processes in which no air volume participates	N	'temporal part of' some 'breathing process' and not ('has participant at some time'some 'volume of air')	N	'temporal part of' some 'breathing process' and not ('has participant' some 'volume of air')	N
PGR_im+	Mary`s blood always has as part some blood cell		history of' value 'Mary`s blood' subClassOf 'has occurrent part' some ('part of occurrent' some ('history of' some 'blood cell'))		'has max' value 'Mary`s blood max' subClassOf 'has continuant part' some 'blood cell'	
	There is a time in which Mary`s blood is devoid of blood cells	N	history of' value 'Mary`s blood' and 'has continuant part at some time' only (not 'blood cell')	Y	'has max' value 'Mary`s blood max' and not ('has continuant part' some 'blood cell')	N
PGR_im-	Joe`s electronic health record always resides on some electronic storage medium		Joe`s health record' Type 'generically depends on at some time' some 'computer storage'	*	'has max' value 'Joe`s health record'_max subClassOf 'generically depends on' some 'computer storage'	
	There is a time in which Joe`s electronic health record is on hard disk A and another time in which it is only on a different storage	Y	'Joe`s health record' 'generically depends on at some time' 'Hard disk A') not ('Joe`s health record' 'generically depends on at some time' 'hard disk A')	N	'max of' some ('generically depends on' some ('has max' value 'Hard disk A max')) and 'max of' some (not ('generically depends on' some ('has max' value 'Hard disk A max')))	Y

	Example	Satisfiability (expected)	TR pattern	Satisfiability TR	TQC pattern	Satisfiability TQC
PGR_ip	Joe`s breathing process has always some volume of air as participant		'temporal part of' value 'Joe`s breathing process' subClassOf 'has occurrent part' some ('part of occurrent' some ('history of' some 'volume of air'))		'temporal part of' value 'Joe`s breathing process' subClassOf 'has participant' some 'volume of air'	
	Joe`s breathing process is without air at some time	N	temporal part of' value 'Joe`s breathing process' and not ('has participant at some time'some 'volume of air')	Y	'temporal part of' value 'Joe`s breathing process' and 'has participant' only (not 'volume of air')	N
PSR_cm+	Every human has a brain and it is always the same brain		human subClassOf 'has continuant part at all times' some brain		human subClassOf 'has max' some ('has continuant part' some brain)	
	There is a time in which Joe does not have his first brain	N	Joe 'has continuant part at some time' 'Joe`s first brain' Joe 'has continuant part at some time' 'Joe`s second brain' not (Joe 'has continuant part at all times' 'Joe`s first brain')	N	'Joe at t2' value not ('has continuant part' some ('has max' value 'Joe`s first brain max')) and ('has continuant part' some ('has max' value 'Joe`s second brain max')	Y
PSR_cm-	Every mammal has the same biological sex during its life		mammal subClassOf ('has quality at all times' some 'biological sex') and (('has quality at all times' only 'male biological sex') or ('has quality at all times' only 'female biological sex'))		mammal and ('has quality' some 'male biological sex') SubClassOf not ('at some time' some ('has quality' only 'female biological sex')) mammal and ('has quality' some 'female biological sex') SubClassOf not ('at some time' some ('has quality' only 'male biological sex'))	
	A mammal that is male at some time and female at some other time	N	mammal and 'has quality at some time' some ('female biological sex') and 'has quality at some time' some 'male biological sex'	Y	mammal and 'at some time' some (mammal and 'has quality' some 'male biological sex') and 'at some time' some (mammal and 'has quality' some 'female biological sex')	Y
PSR_cp1	Every organism always participates in its life, and it is always the same		organism subClassOf 'participates in at all times' some 'biological life'		organism subClassOf 'has max' some ('participates in' some 'biological life')	
	Joe participates in two different lives	N	Joe 'participates in at some time' 'Joe`s first life' Joe 'participates in at some time' 'Joe`s second life' not (Joe 'participates in at some time' 'Joe`s first life')	N	('has max' value 'Joe max') and 'participates in' value 'Joe`s first life' and 'participates in' value 'Joe`s second life'+A35	Y
PSR_cp2	Every biological life always has some organism as participant, and it is always the same		biological life' subClassOf 'has participant at all times' some organism		temporal part of biological life' subClassOf 'has participant' some ('max of' some organism)	
	A life that has for some time a human as participant and for some other time another organism as participant	N	('has participant at some time' some human) and ('has participant at some time' some (not human)) and 'biological life'	Y	('has participant' some human) and ('has participant' some (not human)) and 'biological life'	Y
PSR_im+	Mary has 'Mary`s brain' as a proper part during her lifetime		Mary 'has continuant part at all times' 'Mary`s brain'		'Mary max' Type 'has continuant part' some ('has max' value 'Mary`s brain max')	
	There is a time in which Mary has no brain	N	Mary type 'has continuant part at some time' only (not brain)	N	('has max' value 'Mary max') and not ('has continuant part' some brain)	Y
PSR_im-	Tibbles, a male cat, has the same sex during his life		'Tibbles sex' 'quality of at all times' Tibbles 'Tibbles sex' type Male 'biological sex'		'has max' value 'Tibbles max' SubClassOf ('bearer of' some 'male biological sex') and ('bearer of' only ('male biological sex' or (not ('biological sex'))))	
	Tibbles is female at some time during his life	N	Tibbles type 'has quality at some time' only (not 'male biological sex')	Y	'has max' value 'Tibbles max' and ('bearer of' some 'female biological sex')	N
PSR_ip	Joe participates in his life and not in any other life		Joe Type 'participates in at all times' some 'biological life'		'has max' value 'Joe max' subClassOf 'participates in' value 'Joe`s life'	
	Joe participates in a human life and part of his life is a cat life	N	Joe Type 'participates in at some time' only ('cat life' or not 'biological life') and 'participates in at some time' only ('human life' or not 'biological life')	Y	('has max' value 'Joe max') and 'participates in' some 'cat F38	Y
NR_t	Every fetus is an embryo at some time. Nothing can be both an embryo and a fetus at the same time		fetus disjointWith embryo	*	fetus subClassOf 'at some time' some embryo. embryo disjointWith fetus	
	There are fetuses that were never embryos	N	fetus and not embryo	Y	fetus and not ('at some time' some embryo)	N
NR_i	John was a medical student from 2001-10-01 to 2007-06-30. Every person who is a medical student was a high school student at some time		John Type 'medical student'	*	'medical student' subClassOf 'at some time' some 'high school student' 'John at 2001-10-01 to 2007-06-30 'at some time' 'John max' 'John at 2001-10-01 to 2007-06-30' spans '2001-10-01 to 2007-06-30'	
	John was never a high school student	N	John Type not ('high school student')	Y	'has max' value 'John max' and not ('at some time' some 'high school student')	N