Patterns for representing time-dependent information 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 several design patterns for working around this limitation. Firstly, we describe the use cases motivating the need for an explicit representation of temporality in the context of OWL and biomedical ontologies. Secondly, we propose and discuss different design patterns and evaluate them against the given use cases in the context of their completeness, user friendliness, and performance profile for common reasoning tasks.

Conclusions: In conclusion, we present our recommendations.

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 and data standards communities. It exposes and addresses a weakness of a large number of biomedical ontologies 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 **partOf**, **hasPart**, **participatesIn**, and **instanceOf**. 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* **locationOf** *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:

$$\forall x \forall t : \mathbf{instanceOf}(x, \mathit{RedBloodCell}, t) \rightarrow \exists y : \mathbf{instanceOf}(y, \mathit{OxygenMolecule}, t) \wedge \mathbf{locationOf}(x, y, t) \quad (1)$$

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 relations of parthood, participation and instantiation among many others. The BFO reference specification follows the RO pattern and offers the definitions of these relations, 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 – the two relata (which are particulars), and the time index. However, the OWL language, for reasons of implementation and reasoning efficiency, allows only *binary* relations. Thus, when relations such as **partOf** 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 use cases 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 use cases 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 relationships 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 relationships without clarifying whether the relationships are intended to mean the same thing (e.g. **partOf**, **includedIn**,...). 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

“relationships” or “relations”? I would prefer the latter

intended to be used in multiple ontologies. Both classes and relationships 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 **isTautomerOf** (a chemical relation used in ChEBI) or **isAbout** (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, you and I are both particulars that instantiate the type *Human Being*; a red blood cell in my vein and a white blood cell in yours are both particulars that instantiate the type Cell. Types and classes are often used as synonyms, but there are subtle differences: classes can be defined using the common logical operations such as negation: the result may be a class *Non-smoker*, for which, however, there is no single type it is the extension of.

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 **instanceOf** 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).

(TODO)

Table 1 gives a selection of core BFO classes and their definitions.

Whereas BFO 1.x was restricted to a tree of mutually disjoint classes, BFO 2.0 now offers an extensive

exact number?

set of relations, including **partOf**, **participatesIn**, and **inheresIn**.

(TODO)

Table 2 details these and others together with their definitions. Most of these relations relate individuals, not classes or types, but they may be used in class-level axioms, subject to an appropriate quantification.

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].

More on OWL syntax and semantics (mapping to FOL) for: classes (which are the extensions of BFO types or correspond to logical expressions formed by the extensions of BFO types, so-called defined classes) Individuals (the concrete entities that instantiate BFO types and / or are members of BFO classes).

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 **partOf** `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` **partOf** `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 FOL), 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.

bfo-owl-time-problem

Representing Time

The underspecification of time representations in OWL axioms

Both the OBO axiom

$$\textit{CellMembrane}\ \mathbf{partOf}\ \textit{Cell} \tag{2}$$

and the equivalent OWL axiom

$$\textit{CellMembrane}\ \texttt{subClassOf}\ \mathbf{partOf}\ \texttt{some}\ \textit{Cell} \tag{3}$$

are undefined with regard to time.

The OWL axiom is, but I am not sure whether the OBO axiom is, I also have my concern re OWL - OBO equivalence

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 **partOf** or **locatedIn**, where the suppression of the temporal factor can produce plainly wrong entailments, especially at the level of individuals, such as in the following example:

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

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

$$\mathbf{locatedIn}(\mathbf{Thrombus\#39874}, \mathbf{Patient\#115678}) \tag{5}$$

which follows from the transitivity property of the relation **locatedIn**, 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 axiomatically assume that any ternary relation that holds for a time interval, holds also true for any of its subintervals, including time points.

Formally:

$$\forall a, b, t, t' : \ \mathbf{rel^3}(a, b, t) \wedge \mathbf{within}(t', t) \rightarrow \mathbf{rel^3}(a, b, t') \tag{6}$$

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:

$$\begin{aligned} \mathit{TemporarilyRelated}(A, B) =_{def} \forall a, t : \ & \mathbf{inst^3}(A, a, t) \\ & \rightarrow \exists b, t' : \ (\mathbf{inst^3}(B, b, t') \wedge \mathbf{rel^3}(a, b, t') \wedge \mathbf{within}(t', t)) \end{aligned} \tag{7}$$

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.

$$\begin{aligned} \mathit{PermanentlyGenericallyRelated}(A,B) =_{def} \forall a,t:\ &\mathbf{inst^3}(A,a,t) \\ &\rightarrow \exists b:\ (\mathbf{inst^3}(B,b,t) \land \mathbf{rel^3}(a,b,t)) \end{aligned} \tag{8}$$

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.

$$\begin{aligned} \mathit{PermanentlySpecificallyRelated}(A,B) =_{def}\ &\forall a,t:\ \mathbf{inst^3}(A,a,t) \\ &\rightarrow \exists b:\ \big(\mathbf{inst^3}(B,b,t) \land \mathbf{rel^3}(a,b,t)) \\ &\land \forall t':(\mathbf{inst^3}(A,a,t') \rightarrow (\mathbf{rel^3}(a,b,t') \land \mathbf{inst^3}(B,b,t'))\big) \end{aligned} \tag{9}$$

Methods

bfo-owl-time-use-cases

Overview

The metholology we pursue in this work serves one major goal, *viz.* to find an optimal way to represent time-related aspects in OWL ontologies. It can be summarized as follows:

- Formulation of time-sensitive use cases and competency questions, which represent typical representational tasks and reasoning requirements
- Formalization of the first approach (Temporalized Relations), which embeds time aspects into OWL object properties.
- Formalization of the second approach (Temporally Qualified Continuants), which represents time aspects by temporal slices of continuants.

The results will the consist in corresponding OWL models on which the use cases and competency questions will be tested.

Use Cases and Competency Questions

The following use cases (UC) and competency questions (CQ) will be used for a comparison of the two representational approaches we are proposing.

The use cases will be structured as follows: For each temporal mode of existence (STR, PGR, PSR) we will have four use cases: 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 use case for a non-rigid class.

- STR_cm+: Every tooth is part of an organism at some time. Challenged by:

  "tooth that is never part of an organism": insatisfiable

  "tooth that is part of something that is not an organism or organism part": satisfiable

- STR_cm-: Every apple is green at some time

  Challenged by:

  "apple that is never green": insatisfiable

  "apple that is red at all times": insatisfiable

- STR_cp1: Every vertebrate participates in some birth process at some time

  Challenged by:

  "Vertebrate that never participates in any birth process": insatisfiable

  "Vertebrate that at some time does not participate in a birth process": insatisfiable

- 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": insatisfiable

  "Phase of fecundation in which there is no spermatozoon participating": satisfiable

- STR_im+: The blood specimen #bs430912 is in the lab #lab996 during the whole time interval #20131020

  Challenged by:

  "The blood specimen #bs430912 is in the lab #lab100 during the whole time interval #20131020. Both labs do not share parts" → unsatifiable

- STR_im-: Joe's left ankle is swollen during the whole time interval #20131020

Challenged by:

"Joe's left ankle is not during the whole time interval #20131021" → satifiable

"Joe's left ankle during the whole time interval #20131020 is not swollen" → unsatifiable

- STR_ip: Mary participated in the process Mary's birth

  Challenged by:

  "There is a time in which Mary is not a participant of her birth" → satifiable

- PGR_cm+: Every red blood cell always includes some oxygen molecule

  Challenged by:

  "There are red blood cells without oxygen molecules" → unsatifiable

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

  Challenged by:

  "There are electronic health record that are not on a computer storage" → unsatifiable

- PGR_cp1: Every ?

  any idea?

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

  Challenged by:

  "There are breathing processes in which no air volume participates" → unsatifiable

- PGR_im+: Mary's blood always consists of some blood cell

  Challenged by:

  "There is a time in which Mary's blood is devoid of blood cells" → unsatifiable

- 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 is not on an electronic storage" → unsatifiable

- 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" → unsatifiable

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

  Challenged by:

  "A human who has more than one brain" → unsatisfiable

  "This is rather tricky with TQC. One could express it as: for all temporal instances of Human there is always some temporal instance of brain related. For all human instance which has the same "max" all related brain instances must also have the same "max" "

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

  Challenged by:

  "A mammal that has more than one sex" → unsatisfiable

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

  Challenged by:

  "An organism that 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 more than one organism as participant" → unsatisfiable

- PSR_im+: Mary has 'Mary's brain' as a proper part during her lifetime

  Challenged by:

  "Mary gets a new brain during her lifetime" → unsatisfiable

- PSR_im-: Tibbles has the same sex during his life

  Challenged by:

  "Tibbles changes his sex during his life" → unsatisfiable

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

  Challenged by:

  "Joe participates in more than one 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. Vertebrate embryoes have a chorda at some time

  Challenged by:

  "There are fetuses that were never embryoes" → unsatisfiable

- NR_i: John was a medical student from 2001-10-01 to 2007-06-30

  Challenged by:

  "Every person which is a medical student was a high school student at some time" John was never a high school student. → unsatisfiable

  For the implementation of the use cases and competency questions as OWL axioms see supplementary data.

Evaluation methods

We will use these use cases and competency questions to evaluate two proposed design patterns for temporalization against the following functional criteria:

1. technical completeness,
2. user friendliness, and
3. performance profile

Proposed Design Patterns

Temporalized Relations (TR)

bfo-owl-time-temporalizedrelations

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, such as 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., my body mass is permanently inherent in my 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:

$$\mathbf{rel\_at\_some\_time^2}(a, b) =_{def} \exists t : \mathbf{rel^3}(a, b, t) \tag{10}$$

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

$$\mathbf{locatedIn\_at\_some\_time^2}\ (\mathrm{BarackObama}, \mathrm{AirForceOne}) \tag{11}$$

or in the class-level axiom

$$\forall a:\ \mathbf{inst^2}(\mathit{Leaf}, a) \rightarrow \exists b:\ \mathbf{inst^2}(\mathit{Tree}, b) \wedge \mathbf{part\_of\_at\_some\_time^2}(a, b) \tag{12}$$

with

$$\mathbf{inst^2}(A, a) =_{def} \forall t : \mathbf{inst^3}(A, a, t) \tag{13}$$

The PSR pattern is introduced as follows:

$$\mathbf{rel\_at\_all\_times^2}(a, b) =_{def} \forall t :\ (\mathbf{exists\_at^2}(a, t)\ \rightarrow\ \mathbf{exists\_at^2}(b, t)\ \wedge\ \mathbf{rel^3}(a, b, t)) \tag{14}$$

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

$$\mathbf{locatedIn\_at\_all\_times^2}\ (\mathrm{Earth}, \mathrm{Solar\_System}) \tag{15}$$

or in the class-level axiom

$$\forall a:\ \mathbf{inst^2}(\mathit{Vertebrate}, a) \rightarrow \exists b:\ \mathbf{inst^2}(\mathit{Spine}, b) \wedge \mathbf{has\_part\_at\_all\_times^2}(a, b) \tag{16}$$

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.

$$\mathbf{rel^3}(a, b, t)\ \wedge\ \mathbf{rel^3}(b, c, t) \rightarrow\ \mathbf{rel^3}(a, c, t) \tag{17}$$

the derived binary STR relation is not, because the implied time argument (cf. Formula 10) is not the same 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 Center at some time this does not imply that Obama was at that Center at any time. Yet there is no problem with inverse STR relations.

$$\mathbf{rel^3}(a, b, t)\ =\ \mathbf{inv\_rel^3}(b, a, t) \tag{18}$$

trivially entails

$$\mathbf{rel^2}(a, b)\ =\ \mathbf{inv\_rel^2}(b, a) \tag{19}$$

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 precludes that the second one outlives the first one. If we say that a certain vertebrate has always a spine this does not preclude the the spine may still exist centuries after the animal's death. This means that the inverse of **hasPart_at_some_time^2** is not **partOf_at_some_time^2**, but something like **partOf_at_some_time_at_which_the_whole_exists^2**.

So far we have not considered the PGR case. Note that this was introduced as the standard interpretation of class-to-class relations in OBO in the RO paper, which means that 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. 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 my 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 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 a 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:*hasPart* 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 threedimensional spatial extention 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_history²** relation (inverse: **history_of²**.

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,being **temporal_part_of²** a relation that holds between two occurrents when the former is a phase or subprocess (a slice or segment) of the latter. **occurrent_part_of²** is the general inclusion relation between two occurrents.

$$
\begin{aligned}
&\mathit{PermanentlyGenericallyPartOf}(A,B) =_{def} \\
&\qquad \forall h_p, h, a, t : \mathbf{inst^2}(\mathit{History}, h) \wedge \mathbf{inst^2}(\mathit{Occurrent}, h_p) \wedge \mathbf{inst^3}(A, a, t) \wedge \\
&\qquad \mathbf{temporalPartOf^2}(h_p, h) \wedge \mathbf{historyOf^2}(h, a) \\
&\qquad \rightarrow \exists o, j_p, j, b : \mathbf{inst^2}(\mathit{Occurrent}, o) \wedge \mathbf{inst^2}(\mathit{Occurrent}, j_p) \wedge \\
&\qquad\quad \mathbf{inst^2}(\mathit{History}, j) \wedge \mathbf{inst^3}(B, b, t) \wedge \mathbf{occurrentPartOf^2}(o, h_p) \wedge \\
&\qquad\quad \mathbf{occurrentPartOf^2}(h_p, h) \wedge \mathbf{historyOf^2}(h, b)
\end{aligned} \tag{20}
$$

However, the inclusion of history phases does not allow a distinction between location and parthood (CITE: Jansen&Schulz Mereology), 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 follwing 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)

bfo-owl-time-temporallyqualcontinuants

We can define a *temporal qualification* of a continuant as the result of regarding the continuant in as far as it exists only within a certain portion of time. A temporal qualification of a continuant 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 an OWL knowledge base 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 instance in the world that is being modelled. All of the different temporal qualifications of the same continuant entity share the property of having the same maximal temporal qualification.

The following additional relations are introduced into the ontology to support modelling the temporal qualification of continuants:

- **hasMax** (inverse **maxOf**) relates a TQC instance to its related instance with the maximal temporal extension (which may be itself)
- **atSomeTime** relates a TQC with each other TQC that represents the same continuant
- Note that **atSomeTime** $\equiv$ **hasMax** $\circ$ **maxOf**
- **maxOf** `subPropertyOf` **atSomeTime** (not necessary if hasMax is reflexive)
- **hasTime** relates a TQC with its defining temporal region.

All TQCs must have exactly one temporal region (thus, the **hasTime** relation is 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 instantiation of a TQC. However, implementers may wish to assume for the sake of usability that when instances of continuants are created in an OWL knowledge base 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 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^{TQ} (represented in FOL).

$$\forall x: \ (\mathbf{inst^2}(A^{TQ}, x) \rightarrow \exists a, t_0, t_1: \ (\mathbf{inst^3}(A, a, t_0) \land \mathbf{equals}(x, a, t_1) \land \mathbf{within}(t_1, t_0))) \tag{21}$$

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

$$\forall x \ \mathbf{inst^2}(A^{TQ}, x) \rightarrow \exists a, t: \ (\mathbf{inst^3}(A, a, t) \land \mathbf{hasMax^2}(a, x)) \tag{22}$$

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 standard 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:

introduce the meaning of <.,.> YES, WE DID IT ABOVE (a TQC is a tuple...)

$$\begin{aligned} SomeTimeRelated(A, B) =_{def} \ & \forall a, t: \ \mathbf{inst^2}(A, \langle a, t \rangle) \\ & \rightarrow \exists b, t_1: \ (\mathbf{inst^2}(B \langle b, t_1 \rangle) \land \mathbf{rel^2}(\langle a, t_1 \rangle, \langle b, t_1 \rangle) \land \mathbf{within}(t_1, t)) \end{aligned} \tag{23}$$

specify the meaning of "within" DID ABOVE

We then use the $\mathbf{atSomeTime^2}$ and $\mathbf{hasMax^2}$ relations and the TQC notation to eliminate the tuples:

$$\begin{aligned} SomeTimeRelated(A, B) =_{def} \ & \forall x: \ \mathbf{inst^2}(A^{TQ}, x) \rightarrow \exists y, z \ \mathbf{inst^2}(A^{TQ}, y) \land \\ & \mathbf{inst^2}(B^{TQ}, z) \land \mathbf{atSomeTime^2}(y, x) \land \mathbf{rel^2}(y, z) \end{aligned} \tag{24}$$

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 $\mathbf{rel^2}$ in the above to ensure that the portions of time are appropriately overlapping, since $\mathbf{rel^3}$ holds at one time only:

$$\forall x, y : \mathbf{rel^2}(x, y) \rightarrow \exists t, t_1 : \ (\mathbf{hasTime^2}(x, t) \wedge \mathbf{hasTime^2}(y, t_1) \wedge \mathbf{within}(t_1, t)) \tag{25}$$

Now we have derived a binary expression $\mathbf{rel^2}$ we are free to use this in OWL axioms. Temporary relatedness is thus expressed in OWL as follows:

$$A^{TQ} \ \texttt{subClassOf} \ \mathbf{atSomeTime^2} \ \texttt{some}(\mathbf{rel^2} \ \texttt{some} \ B^{TQ}) \tag{26}$$

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

FIX FOR NEW APPROACH

$$A \ \texttt{hasKey}(\mathbf{hasMax^2}) \tag{27}$$

A Box issues to be discussed separately ?

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:

$$\forall x : \ \mathbf{inst^2}(A^{TQ}, x) \rightarrow \exists y : \ \mathbf{inst^2}(B^{TQ}, y) \wedge \mathbf{rel^2}(x, y) \tag{28}$$

Informally, this means that, whatever temporal qualification of an instance of A we choose, it will alway 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:

$$A^{TQ} \ \texttt{subClassOf} \ \mathbf{rel^2} \ \texttt{some} \ B^{TQ} \tag{29}$$

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

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:

UPGRADE PROPOSAL TO LATEST TQC VERSION, i.e. remove continuantOf relation

$$\begin{aligned}
&\forall x:\ \mathbf{inst^2}(A^{TQ}, x) \rightarrow \\
&\quad \exists y: \mathbf{inst^2}(B^{TQ}, y) \wedge \mathbf{rel^2}(x, y) \wedge \\
&\quad\quad \forall x_1, a:\ ((\mathbf{inst^2}(A^{TQ}, x_1) \wedge \mathbf{continuantOf^2}(a, x) \wedge \mathbf{continuantOf^2}(a, x_1)) \wedge \\
&\quad\quad\ \exists y_1, b:\ (\mathbf{inst^2}(B^{TQ}, y_1)\mathbf{continuantOf^2}(b, y) \wedge \mathbf{continuantOf^2}(b, y_1) \wedge \\
&\quad\quad\ \mathbf{rel^2}(x_1, y_1)))
\end{aligned} \tag{30}$$

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

Discussion

bfo-owl-time-discussion

Nice and good evaluation of the different approaches goes here

many of the issues raised by Alan and Chris in the mailing list discussions

Survey of existing approaches

Histories in BFO 2

In BFO 2, work is under way to sketch 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." [14] This means that there is a one to one correspondence between continuants and certain processes, which effectively provides a "bridge" between the 3D and the 4D perspective. No complete formal theory of histories, which have previously been described in [15], 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 **hasPart** is transitive, and used in axioms such as

$$\mathit{Lung}\ \texttt{subClassOf}\ \mathbf{hasPart}\ \texttt{some}\ \mathit{LobeOfLung} \tag{31}$$

and

$$\mathit{LobeOfLung}\ \texttt{subClassOf}\ \mathbf{hasPart}\ \texttt{some}\ \mathit{BronchiopulmonarySegment} \tag{32}$$

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

I fused the default interpretation with the "standard" interpretation. Both mean the same IMHO

It is surprising that 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.

Check this argument

.

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

$$\forall t:\ \langle a^{\mathcal{I}}, t\rangle \in \Delta^{\mathcal{I}} \rightarrow \langle a^{\mathcal{I}}, t\rangle \in C^{\mathcal{I}} \tag{33}$$

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 [16] to ease comparison with the specified semantics [12].

Existential quantification ($\mathbf{rel^2}$ `some` B)

$$\begin{aligned} &\text{ObjectSomeValuesFrom}(\mathbf{rel^2}, B)^{\mathcal{I}} =_{def} \\ &\qquad \{\langle a^{\mathcal{I}}, t\rangle \in \Delta^{\mathcal{I}} \mid \exists b:\ \langle a^{\mathcal{I}}, b, t\rangle \in \mathbf{rel^3}^{\mathcal{I}} \wedge \langle b, t\rangle \in B^{\mathcal{I}}\} \end{aligned} \tag{34}$$

Value restriction ($\mathbf{rel^2}$ `only` B)

$$\begin{aligned} &\text{ObjectAllValuesFrom}(\mathbf{rel^2}, B)^{\mathcal{I}} =_{def} \\ &\qquad \{\langle a^{\mathcal{I}}, t\rangle \in \Delta^{\mathcal{I}} \mid \forall b:\ \langle a^{\mathcal{I}}, b, t\rangle \in \mathbf{rel^3}^{\mathcal{I}} \rightarrow \langle b, t\rangle \in B^{\mathcal{I}}\} \end{aligned} \tag{35}$$

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

$$\text{ObjectPropertyAssertion}(\mathbf{rel^2}, a, b) =_{def}\ \forall t:\ \langle a^{\mathcal{I}}, t\rangle \in \Delta^{\mathcal{I}} \rightarrow \langle a^{\mathcal{I}}, b^{\mathcal{I}}, t\rangle \in \mathbf{rel^3}^{\mathcal{I}} \tag{36}$$

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 1 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

Table 1: Syntactical representations of (permanent) relatedness expressions

OBO Syntax	OWL (Manchester Syntax)	First Order Logic
`[Term]` `id:` A `relationship:` $\mathbf{rel^2}$ B	A `subClassOf` $\mathbf{rel^2}$`some`B	$\forall a, t: \mathbf{inst^3}(A, a, t) \rightarrow$ $\big(\exists b: \mathbf{inst^3}(B, b, t) \wedge$ $\mathbf{rel^3}(a, b, t)\big)$

relation **hasPart**: if an organism has some heart at any time, and if this heart has some heart valve at any time, then the organism has some heart valve at any time:

$$\frac{A \texttt{ subClassOf } \mathbf{hasPart^2} \texttt{ some } B \qquad B \texttt{ subClassOf } \mathbf{hasPart^2} \texttt{ some } C}{A \texttt{ subClassOf } \mathbf{hasPart^2} \texttt{ some } C}$$

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 $C_{\mathbf{rel^3}}$ for each ternary relation $\mathbf{rel^3}$. The relata of $\mathbf{rel^3}$ are then connected to instances of $C_{\mathbf{rel^3}}$ by three new binary relations $\mathbf{R_1^2}$, $\mathbf{R_2^2}$, $\mathbf{R_3^2}$. The instance-level assertion

$$\mathbf{rel^3}(a, b, t)$$

would then be transformed into the following statement:

Changed from list of statements to proper axiom

$$\exists x : C_{\mathbf{rel^3}}(x) \wedge \mathbf{R_1^2}(x, a) \wedge \mathbf{R_2^2}(x, b) \wedge \mathbf{R_3^2}(x, t) \tag{37}$$

Such proposals have, with a varying degree of sophistication, seen quite a bit of dissemination in the ontology engineering community [17], 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 [18]. 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 [19].

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 [20]. 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 (38).

$$\textit{Leaf}\ \texttt{subClassOf}\ \texttt{inverseOf}(\mathbf{timeSliceOf^2})\ \texttt{some}\ (\mathbf{hasPart^2}\ \texttt{some}\ (\mathbf{timeSliceOf^2}\ \texttt{some}\ \textit{Tree})) \qquad (38)$$

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 $\texttt{inverseOf}(\mathbf{timeSliceOf^2})$ `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 treatment of contingent properties [21]. 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 [20], 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 [22] 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 $\mathbf{hasTimeStamp^2}$, $\mathbf{hasSubject^2}$, and $\mathbf{hasObject^2}$, the axiom

$$S\ \texttt{hasKey}(\mathbf{hasTimeStamp^2}, \mathbf{hasSubject^2}, \mathbf{hasObject^2}) \tag{39}$$

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

0.1 Performance

Setting the hasMax relation to be functional creates problems with the reasoning with Fact++ as it appears not to terminate when executed, while HermiT does terminate. (Check). Setting hasMax and maxOf to be reflexive causes an inconsistency (explanations hint at an interference with existsAt).

0.2 Relevance (or not) to other top-level ontologies

Conclusions

Summary

Recommendations of which approach to follow under which circumstances

Author's contributions

Every author made very important contributions to everything.

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Figures

Figure 1 - Sample figure title

A short description of the figure content should go here.

Figure 2 - Sample figure title

Figure legend text.

Tables

Table 1 - BFO Classes

In this table we present the core BFO classes with their definitions.

BFO Classes	
A1	B2
A2	...
A3	..

Table 2 - BFO Relations

In this table we present a selection of BFO relations together with their definitions.

BFO Relations		
A1	B2	C3
A2	...	..
A3	..	.