Expressing time-dependent relations without explicitly referring to time

A contribution to the OWL version of BFO 2.0

Author: Stefan Schulz, Graz
Contributor: Janna Hastings, Geneva
Contributor: Niels Grewe, Rostock
Contributor: Ludger Jansen, Rostock
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Problem

Continuants not only persist, but also change over time. Any relational expression which makes reference to a particular continuant can have different truth values at different times and would therefore be ambiguous if not referring to time. For example, each of the following pairs of statements may be true together:

- A ripening apple:
  inheresIn (Apple_123, GreenColor_123, 2011-06-20), and
  inheresIn (Apple_123, RedColor_123, 2011-07-01)
- Joe's appendectomy:
  partOf (Joe's_Appendix, Joe, 2011-08-25), and
  not (**partOf** (Joe's_Appendix, Joe, 2011-08-26))
- Mary's arriving late at a performance of Beethoven's 9 th symphony:
  not (**participatesIn** (Mary, Beethoven_9th_Symphony_Performance_1234, 2012-01-01:20:05))
  participatesIn (Mary, Beethoven_9th_Symphony_Performance_1234, 2012-01-01:20:55)

All statements asserting the relation between two entities at least one of which can change through time must therefore be time indexed.

Description logics allow only binary relations between individuals, called object properties. If a ternary relation with explicit time reference is expressed as a binary object property without such reference, an expression such as

A subClassOf **rel** some B[1]

can be interpreted in different ways based on the "temporal strength" of the relational term "**rel**" (**inst** being the instantiation relation between an individual and a class at some point in time t):

(I) For each instance of A there is some instance of B to which A is related by **rel** at some time.
$\forall a, t_1 \exists t_2$: **inst** $(a, A, t_1) \wedge$ **inst** $(a, A, t_2) \rightarrow \exists b$, (**inst** $(b, B, t_2) \wedge$ **rel** (a, b, t_1))
Example: All apples are green at some time.
We will call this case "temporarily related".

(II) For each instance of A there is some instance of B at all times related by **rel.**
$\forall a, t$: **inst** $(a, A, t) \rightarrow \exists b$: **inst** $(b, B, t) \wedge$ **rel** (a, b, t)

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[1] Throughout the paper, we will use "**rel**" as an example and general placeholder for concrete relations used in an ontology. Unless otherwise noted, description logic formulas appear in Manchester syntax, while formulas that assume no particular logical formalism are presented in a first order logic notation.

Example: All cells always contain some water molecule (although not always the same one).
We will call this case "permanently generically related".

(III) For each instance of A there is some (and always the same) instance of B at all times related by **rel.**
$\forall$a, t_1, t_2: **inst** (a, A, t_1) $\wedge$ **inst** (a, A, t_2) $\rightarrow$ $\exists$b: **inst** (b, B) $\wedge$ **rel** (a, b, t_1) $\wedge$ **rel** (a, b, t_2)
Example: All cells always have a cell membrane (and always the same one).
We will call this case "permanently specifically related".

(IV) **rel** itself is a time indexed relation, e.g. **inheresInAt2011-06-20** and only makes assertions about that particular timepoint t_0.
$\forall$a: **inst** (a, A, t_0) $\rightarrow$ $\exists$b: **inst** (b, B, t_0) $\wedge$ $\mathbf{rel_{t0}}$ (a, b)
Example: All instances of a newly manufactured chemical are located in a lab *at the moment of their creation*.
We will call this case "instantaneously related".

Our working hypothesis will be that the interpretations *"temporarily related"* (I) and *"permanently generically related"* (II) are the ones most relevant in the context of application ontologies. The interpretation (III), viz. "*permanently specifically related"*, is a special case of *"permanently generically related"*.

Connection to the SNAP/SPAN distinction

BFO has traditionally maintained a strong distinction between 3D and 4D accounts of reality.[2] According to BFO, a 3D description of reality accounts for our intuition of a strong distinction between spatial and temporal phenomena, e.g. objects that persist through time, while a four-dimensionalist view coalesces both into a spatiotemporal account, where, for example, objects are conceived as something like "space-time worms". But despite its insistence on this distinction, BFO maintains that it does not imply the existence of two incompatible descriptions of reality, but that the 3D and the 4D view instead describe two complementary facets of reality. Consequentially, the ontological account of BFO is partitioned into two kinds of constituent ontologies. There is, on the one hand, a series of 3D ontologies, which can basically be thought of as "snapshots" of reality at a given point in time and are hence called SNAP ontologies. The overaching four-dimensional picture is on the other hand provided by a so called SPAN ontology, to which all entities from SNAP ontologies are related through their lifes or histories.

It is easy to see that interpretation (IV) above belongs to SNAP ontologies proper because it describes the state of the world at one particular moment in time. It also highlights some severe impendance mismatch between the theoretical framework of BFO and the constraints of OWL 2. The BFO solution is to use time-indexed SNAP ontologies for which a certain relational assertion holds. A similar mechanism is not specified for OWL 2 ontologies nor can the BFO approach be adopted as an informal convention. Assume there are two ontologies, O_0 and O_1, each describing whether the relation **rel** holds between two objects a and b at a different point in time. Now, if in O_0 "**rel**(a,b)" is true, and in O_1, "**rel**(a,b)" is false, we derive a contradiction once we construct a SPAN ontology O_s that imports both O_0 and O_1, due to the fact the object property corresponding to **rel** shares the same namespace in all three ontologies.

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

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[2] Grenon P, Smith B. SNAP and SPAN: Towards Dynamic Spatial Ontology. In: Spatial Cognition And Computation 4: 1 (2004), pp. 69–103.

Possible solutions

1. Adaptation of the description logics interpretation of ternary relations

One solution, which appears to be the most straightforward, is to clarify the interpretation of the description logics constructs used to express class level relations such that it becomes clear that they globally commit to a “for all times” interpretation, or *"permanently generically related"* as introduced above. We do this by presenting an interpretation of OWL 2 that perserves syntactical structure and inferences, but extends the instances of classes and object properties in the OWL model with an additional time index t, which specifies that the entity in question exists at t. In order to keep the surface grammar and overall semantics intact, the interpretations of all OWL axioms will be prepended with a conditionalized universal quantification over t that specifies that the axiom should hold at all times that the entity in question exists. Time instants are hereby external to the domain. For example, the interpretation of a class assertion axiom that asserts that a is an instance of class C, as long as a exists, would then read (domain Δ, interpretation $\mathcal{I}$):

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

The interpretation temporality-sensitive relations will become clear by giving the definitions[3] of existential quantification and value restrictions, which both assert permanently generically 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:

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

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

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

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

In contrast, object property assertions operate on the level of instances and produce permanently specific relatedness:

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

We identify the following advantages:

The interpretation as *"permanently generically related"* corresponds to the OBO semantics[4] of class level relations:

- OBO: A **Rel** B
- OWL: A subClassOf **rel** some B
- FOL: $\forall a, t$: **inst** $(a, A, t) \rightarrow \exists b$: **inst** $(b, B, t) \wedge$ **rel** (a, b, t)

- Quantification over time maintains transitivity of the relation in question. This can be shown, e.g. by the transitive relation **hasPart**: If an organism has some heart at any time, and if this heart has some heart valve at any time, then the organism has some heart valve at any time.

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[3] For better comparability with the OWL 2 specification, it is expedient to format these definitions according to the canonical functional syntax instead of Manchester syntax.

[4] Smith B, Ceusters W, Klagges B, Köhler J, Kumar A, Lomax J, Mungall C, Neuhaus F, Rector AL, Rosse C. Relations in biomedical ontologies. Genome Biology 2005;6 (5):R46. Epub 2005 Apr 28.

$$\frac{\begin{array}{l}\forall a, t\text{: } \mathbf{inst}\ (a, A, t) \rightarrow \exists b\text{: } \mathbf{inst}\ (b, B, t) \wedge \mathbf{hasPart}\ (a, b, t) \\ \forall b, t\text{: } \mathbf{inst}\ (b, B, t) \rightarrow \exists c\text{: } \mathbf{inst}\ (c, C, t) \wedge \mathbf{hasPart}\ (b, c, t)\end{array}}{\forall a, t\text{: } \mathbf{inst}\ (a, A, t) \rightarrow \exists c\text{: } \mathbf{inst}\ (c, C, t) \wedge \mathbf{hasPart}\ (a, c, t)}$$

- This translates into DL in a straightforward and user-friendly way, given the above explication of the interpretation function:

$$\frac{\begin{array}{l}\text{A subClassOf } \mathbf{hasPart} \text{ some B} \\ \text{B subClassOf } \mathbf{hasPart} \text{ some C}\end{array}}{\text{A subClassOf } \mathbf{hasPart} \text{ some C}}$$

On the downside we would have to show that the intended models of OWL 2 would actually be perserved and we also have to acknowledge that this approach does neither provide for *"temporary relatedness"* (I), nor can it be refined in terms of "*permanently specific relatedness*" (III) on the level of classes.

2. Extension of the ontology by additional relations for "some" and "all"

An alternative proposal would, be to disambiguate the term "**rel**" by introducing two distinct relation terms in order to express the possible temporal meanings of a relational assertion by introducing two binary relations to express the ternary one:

"**rel** (a, b, t)"

a) **rel-at-some-time** (a, b) $=_{def}$ $\exists$t: **exists_at**(a, t) $\wedge$ **exists_at**(b, t) $\wedge$ **rel** (a, b, t)
b) **rel-at-all-times** (a, b) $=_{def}$ $\forall$t: **exists_at**(a, t) $\rightarrow$ **rel** (a, b, t) $\wedge$ **exists_at**(b, t)

Whereas a) corresponds to *"temporarily related"*, b) corresponds to *"permanently specifically related"*. The latter one, according to our hitherto analysis, is too strict, as there is no way of expressing *"permanently generically related"*, which – as we have identified – has been the standard OBO interpretation until now. This is because the relationship between a and b holds between two instances – implying that **rel-at-all-times** holds between instance a and instance b at all times. This is obviously false for parthood between cells and water molecules, as well as for many other cases in biology and medicine.

It is thus dubious whether **rel-at-all-times** is at all useful for ontology engineering: As always, one would need to check whether the relational assertion holds universally. So if this relation is asserted now (t_0) between entities a and b that are supposed to exist at any time $t_1 > t_0$, it would be necessary to guarantee that the assertion "a **rel** b" holds in the future, which is usually very difficult. There are only a small number of cases where it is ontologically impossible for a to be related to anything but b. (e.g. the relation of a surface to the body that it is a surface of).

However, the missing (and probably most relevant) case *"permanently generically related"* (III) could still be expressed with the "default" translation as expressed above.

We would then have the following relation hierarchy

- **rel-at-some-time** *(temporarily related)*
  - **rel** *(permanently generically related)*
    - **rel-at-all-times** *(permanently specifically related)*

This hierarchy is sufficient to support subsumption reasoning on classes that differ in the "temporal strength" of their connection to other entities by a variant of **rel**, but does not allow inferences to be drawn based on instance data.

3. Augmenting the ontology with an account of continuant-stages

In their Mereology of Stages and Persistent Entities[5] Bittner and Donnelly have shown that it is possible to distinguish between time-dependent and time-independent parthood relations without referring explicitly to time. Stages are instantaneous spatial entities in the sense that they are confined to a single “time-slice” of a continuant. Therefore a relation between a stage and whatsoever other entity is never ambiguous with regard to time, because it only exists at the moment the stage exists.

By introducing stages, Bittner and Donnelly are able to distinguish between temporary and permanent relatedness, though they restrict the scope of their approach to the analysis of mereological relations between entities or their stages respectively:

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

However, we see no reason for not extending this approach to *all* ternary relations that involve continuants and are sensitive to ambiguities because of different temporal strength. There are, however, binary relations between continuants or their stages that carry implicit reference to time and do not need this kind of treatment. For example

Apple subClassOf **derivesFrom** some AppleSeed

is not in want of an temporalized re-interpretation as **derivesFrom**(Apple$_{ABC}$, AppleSeed$_{ABC}$, t$_{123}$) because it should, in its definition, already specify the temporal order. That is, the derived entity needs to temporally succeed the entity it is derived from.

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

Temporary relatedness

The relation **hasStage** (inverse **stageOf**) relates a continuant with a stage (non-temporally-extended slice) of itself. E.g.,

- 'Apple$_{ABC}$ at t$_{123}$' is a **stageOf** Apple$_{ABC}$
- 'Greenness$_{AppleABC}$ at t$_{123}$' is a **stageOf** Greenness$_{AppleABC}$

Let us consider two classes of continuants A and B and assume that each instance of A has a stage that is related to some B-stage

$$\forall a: \textbf{inst}\ (a, A) \rightarrow \exists p, b, q : \textbf{inst}\ (p, Stage) \wedge \textbf{inst}\ (b, B) \wedge \textbf{inst}\ (q, Stage) \wedge \textbf{stageOf}\ (p, a) \wedge \textbf{rel}\ (p, q) \wedge \textbf{stageOf}\ (q, b)$$

In DL:

A subClassOf **hasStage** some (**rel** some (**stageOf** some B))

Similarly, relations between continuants and occurrents can be construed using stages. For instance, every A could be related to the part of a process O which occurs at the time of the stage:

5 Bittner, T. and Donnelly, M. 2004. 'The mereology of stages and persistent entities', In Lopez de Mantaras, R. and Saitta, L. (ed.): Proceedings of the European Conference of Artificial Intelligence (ECAI04), IOS Press, 283-287.

$$\forall a: \mathbf{inst}\ (a, A) \rightarrow \exists p, o, q: \mathbf{inst}\ (p, \mathrm{Stage}) \wedge \mathbf{inst}\ (o, O) \wedge \mathbf{inst}\ (q, O) \wedge \mathbf{stageOf}\ (p, a) \wedge \mathbf{rel_P}\ (p, q) \wedge \mathbf{processPartOf}(q, o)$$

In DL:

A subClassOf **hasStage** some (**rel$_{\mathbf{P}}$** some (**processPartOf** some O))

Wherever something is related by **rel** to a stage of an entity it is related to that entity though not necessarily in the same sense, therefore,

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

One can than ask how precisely we are to interpret **rel** and **rel*** (and **rel$_{\mathbf{P}}$** and **rel$_{\mathbf{P}}$*** respectively) in terms of the interpretations we presented earlier. Clearly, **rel** in this case holds between two stages of continuants and **rel$_{\mathbf{P}}$** between a continuant stage and a phase of a process. And because stages are not temporally extended, these are relations that obtain only instantaneous and hence constitute a case of instantaneous relatedness (IV). **rel*** on the other hand obtains between a stage and continuant which persists through time and **rel$_{\mathbf{P}}$*** between a stage and a temporally extended occurrent. Hence either makes diachronic reference and could thus be said to establish temporary relatedness (I) between the two entities. We thus, for now, can formulate the following role chains in DL, introducing the new relation **rel-at-one-time** which synchronously relates stages but not temporarily extended continuants:

rel-at-one-time o **stageOf** subrelationOf **rel-at-some-time**
relP-at-one-time o **processPartOf** subrelationOf **rel$_{\mathbf{P}}$-at-some-time**

These can be used to simplify the above expressions to:

A subClassOf **hasStage** some (**rel-at-some-time** some B)
A subClassOf **hasStage** some (**rel$_{\mathbf{P}}$-at-some-time** some O)

Assuming **rel** is transitive, e.g. **hasPart**:

A subClassOf **hasStage** some (**rel-at-some-time** some B)
B subClassOf **hasStage** some (**rel-at-some-time** some C)

there is now no way to infer:

* A subClassOf **hasStage** some (**rel-at-some-time** some C)

This is consistent with the fact that, e.g. an apple a is part of a tree t at t_1, and the same apple, at t_2, after being no longer part of t has a germ g, then g is not part of t at any time.

Permanent relatedness

Permanent relatedness of two entities can be formulated both from the vantage of the stages and from the vantage of the temporally persisting entities. For stages, one would express the fact that each stage of A is related to some B-stage as follows:

$$\forall a, p: \textbf{inst}\ (a, A) \wedge \textbf{inst}\ (p, \text{Stage}) \wedge \textbf{stageOf}\ (p, a) \rightarrow$$
$$\exists b, q : \textbf{inst}\ (b, B) \wedge \textbf{inst}\ (q, \text{Stage}) \wedge \textbf{rel-at-one-time}\ (p, q) \wedge \textbf{stageOf}\ (q, b)$$

Or, in DL:

(**stageOf** some A) subClassOf **rel-at-one-time** some (**stageOf** some B)

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

A subClassOf (**hasStage** only (**rel-at-one-time** some (**stageOf** some B))
and (**hasStage** some (**rel-at-one-time** some (**stageOf** some B)))

Either formulation perserves transitivity if the grounding relation **rel_t** is transitive:

stageOf some A subClassOf **rel_t-at-one-time** some (**stageOf** some B)
stageOf some B subClassOf **rel_t-at-one-time** some (**stageOf** some C)

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stageOf some A subClassOf **rel_t-at-one-time** some (**stageOf** some C)

Adressing User Concerns with the continuant-stage approach

Formulated this way, reference to stages of continuants successfully captures at least the most important forms of time-indexed relatedness (i.e. (I) and (II)) but it seems to have a number of downsides, especially if one takes into account that fact that for proper formulation one will have to

1. include **stageOf** and **hasStage** as object properties which are marked as functional or inverse functional respectively, which might cause some performance penalty for reasoning.
2. specify property chains for all relations included in the ontology. This effectively turns them into composite properties as per section 11 of the OWL 2 structural specification, which also imposes the restriction that composite properties are not to be used in cardinality restrictions.[6] Since the pattern described here is suggested for inclusion into a top level ontology, this imposes a significant additional expressivity limit on unsuspecting users, the impact of which should be carefully evaluated.
3. force users to apply complex, suffixed relation names when modeling, something that might also be undesirable when users migrate from an old version of BFO to one that adopts a stage account of temporally-relativized relatedness.
4. deal with the fact that it, to some degree blurs the distinction between continuants and occurrents.

The most user-visible point would be 3., which is fortunately also the easiest to deal with. This can be done by leveraging semantically rich definitions in the property hierarchy to “hide” the suffixed relations while still retaining their specific interpretations. Apart from the reusable relations **hasStage** and **stageOf**, we introduce for each relation **rel** with a domain D and a range R, where D_Stage and R_Stage are classes of stages of D and R respectively, the following structure into the ontology:

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[6] Motik B, Patel-Schneider PF, Parsia B. OWL 2 Web Ontology Language Structural Specification and Functional-Style Syntax. 2009. http://www.w3.org/TR/2009/REC-owl2-syntax-20091027/

Property name	Superproperty	Domain	Range	Property Chain
rel	(as per ontology)	D or D_Stage	R or R_Stage	
rel-at-one-time	**rel**	D_Stage	R_Stage	
rel-at-some-time	**rel**	D_Stage	R	**rel-at-one-time** o **stageOf**
rel-at-all-times	**rel**	D	R	

This way, the distinction between temporary relatedness and permanent generic relatedness can be made by just using **hasStage** and **rel**:

(1) D is temporarily **rel**-related to R: D subClassOf **hasStage** some (**rel** some R)

(2) D is permanently **rel**-related to R: D subClassOf some (**rel** some R)

It is straightforward to see that in (1) **rel** is in fact the more specific type **rel-at-some-time** because it is the only subproperty that holds between a stage and a continuant. Unfortunately, OWL 2 does not allow disjoint unions of object properties to be directly formulated, hence the following general class axiom is required for the inference:

(a) (**rel** some owl:Thing) EquivalentTo
((**rel-at-one-time** some Thing) or (**rel-at-some-time** some Thing) or (**rel-at-all-times** some Thing))

By the same reasoning (2), **rel-at-all-times**, which clearly models interpretation (II), can be inferred to be of the correct relationship type. But this only holds by virtue of the domain/range restriction and the disjointness axiom, which is a bit too weak to form a compelling ontological model, especially since it does not say anything about the stages of the continuants. Instead, one would want to make sure that **rel-at-all-times** only holds when for every stage of D instance, there exists an R instance to which it is connected by **rel-at-one-time**. Again, this is not achievable with object properties alone but requires the following general class axiom:

(b) D and (**rel** some R) EquivalentTo
(**hasStage** some (**rel-at-one-time** some (**stageOf** some R))) and (**hasStage** only (**rel-at-one-time** some (**stageOf** some R)))

None of these axioms or complex definitions of the time-indexed relation variants need ever to be explicitly used in an ontology, in fact they could even be hidden by placing them in a special deep-semantic layer ontology that can be imported into the “normal” top-level to provide additional semantic accuracy.

Recommendation

There are two modeling approaches for the most "normal" interpretation of time-indexed relatedness, namely what we have introduced as permanently related (II). Whereas the latter pattern using continuant-stages is semantically clearer as it does not simplify ternary relations, it seems too complex to be recommended for use in application ontologies, but that complexity can – to a great extend – be hidden from the user, which makes this technique seem feasible. Still, a refinement of the DL interpretation function accounting for time-indexed ternary relations would suit the requirements equally well, even though it cannot express temporary relatedness (I).

Since we acknowledge the importance of temporary relatedness, the stage account is at a slight advantage expressivity-wise. But, still, it cannot account for interpretation (III), viz. strict permanent relation, which means that each instance of A is permanently related to always the same instance of B cannot be captured in this proposal because it exceeds the expressiveness of DL to state with this modeling approach. If needed, it could be expressed by a subrelation with a specific assigned interpretation. However, its usefulness should be thoroughly analyzed under ontological scrutiny, due to its commitment to time points that lie in the future.