Time in RDF

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Time in RDF

Some approaches to introduce time in RDF

a) Theoretical works

- Extending RDF and OWL with validity time (Gutierrez et al., 2007) (Motik, 2012)
- Temporal description logics (Lutz et Wolter, 2008)

b) Practical approaches

- Reification
- Named graphs
- 4D fluents
- n-ary relation patterns

Time

Two temporal dimensions

Valid time is the time when data is valid in the modeled world;
Transaction time is the time when data is actually stored in the database.

- The versioning approach captures transaction time
- Labeling is mostly used when representing valid time.

Introducing time into RDF

Reference: Gutierrez, C., Hurtado, C. A., & Vaisman, A. (2007). Introducing time into RDF. IEEE Transactions on Knowledge and Data Engineering, 19(2), 207–218.

Temporal Domain

- Point-based temporal domain
- Encode time-points in intervals when possible (clarity)
- Time as a discrete, linearly ordered domain,
  - as usual in virtually all temporal database applications.
- $[a, b]$ with $a \leq b$, denotes the closed interval from a to b, i.e $[a, a+1, a+2, \ldots, b]$.

Temporal Graph Definition

- A temporal triple is an RDF triple (a, b, c) with a temporal label t (a natural number).
  - Notation (a,b,c)[t].
  - $(a, b, c)[t_1, t_2]$ denotes $\{(a, b, c)[t] \mid t_1 \leq t \leq t_2\}$
- A temporal graph is a set of temporal triples.

Operations

$G|_t$, the slice at t, $\{(a,b,c)[u] \in G \mid u = t\}$ all temporal triples with temporal label t.

$u(G)$, the underlying graph of G, is the set $\{(a,b,c) \mid (a,b,c)[t] \in G \text{ for some } t\}$

$G(t)$, the snapshot of G at t, $G(t) \stackrel{def}{=} u(G|_t)$

Temporal entailment

For ground temporal RDF graphs (no blank nodes)

$G_1 \models_{time} G_2$
if and only if $G_1(t) \models G_2(t)$ for each t

For arbitrary temporal RDF graphs

$G_1 \models_{time} G_2$
if and only if for every ground instance $\mu_1(G_1)$ there exists a ground instance $\mu_2(G_2)$ such that $\mu_1 G_1 \models_{time} \mu_2 G_2$.

Example

(X, Y are blank nodes)
$G_1 = \{(a, b, X)[3], (a, b, X)[4]\}$
$G_2 = \{(a, b, Y)[3], (a, b, X)[4]\}$

Entailments

$G_1 \models_{time} G_2$
$G_2 \not\models_{time} G_1$ (e.g. take $\mu_2(Y) = d, \mu_2(X) = e$, and $d \neq e$

Problem with blank nodes

$G_1(t) \models G_2(t)$ for each t does not imply $G_1 \models_{time} G_2$

- A blank node represents the same (unnamed) resource throughout the time range, rather than a sequence of different resources.
- Different from the classical setting.
- Temporal marks are not only a relation among fixed objects, but also among time-varying objects, the blank nodes.

Time arithmetics

- The notion of entailment for temporal RDF needs a basic arithmetic of intervals in order to combine the notion of temporality and deductive properties. For example,
  - if we have (a, subClassOf, c)[2; 3]; (c, subClassOf, d)[2],
  - then we should be able to derive (a, subClassOf, d)[2],
  - but not (a, subClassOf, d)[3]

Anonymous time

- To study temporal graphs that contain triples of the form $(a, b, c)[X]$, where X is an anonymous timestamp,
- State that the triple (a, b, c) is valid in some unknown time.
- ! The set of anonymous timestamps and blank nodes are disjoint;

- anonymous timestamps can be used to state that a set of triples occurred at the same time, even though their valid time is unknown.
  - $(a, b, c)[T], (a, b', c')[T]$
- A standard RDF graph can be made temporal by means of anonymous timestamps and, thus, modeled as temporal graphs.

Entailment

$$G_1 \models_{timegen} G_2$$

if and only if for each t-ground graph $\mu_1(G_1)$ (all the anonymous times have been replaced by time values), there is a t-ground graph $\mu_2(G_2)$ such that

$$\mu_1(G_1) \models_{time} \mu_2(G_2)$$

Examples

.

$$\{(a; subClassOf; b)[T_1]; (b; subClassOf; c)[T_1]\}$$

$$\models_{timegen} \{(a; subClassOf; c)[T_2]\}$$

But it is not the case that

$$\{(a; subClassOf; b)[T_2]; (b; subClassOf; c)[t_1]\}$$

$$\models_{timegen} \{(a; subClassOf; c)[T_2]\}$$

Query language

"Find the service providers who have offered a Web service between time instants 0 and 2, and return them qualified by early providers."

$$(?X, \mathit{type}, \mathit{earlyProvider}) \leftarrow (?X, \mathit{type}, \mathit{serviceProvider})[?T], (?S, \mathit{providedBy}, ?X)[?T], 0 \leq ?T, ?T \leq 2$$

asking for a snapshot of the graph at time 2, we have:

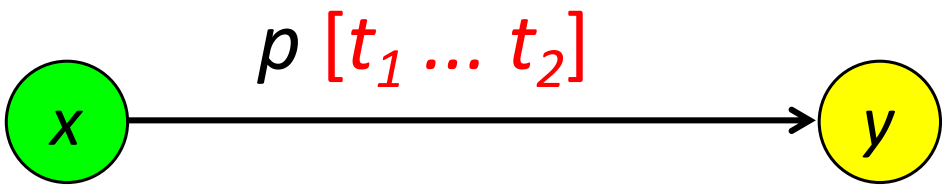
$$(?X; ?Y; ?Z) \leftarrow (?X; ?Y; ?Z)[2]$$

"Find the services providers, along with the Web services they have offered, and the time instants when this occurred."

$$(?X; \mathit{hasprovided}; ?Y)[?T] \leftarrow (?Y; \mathit{providedby}; ?X)[?T]$$

Practical approaches

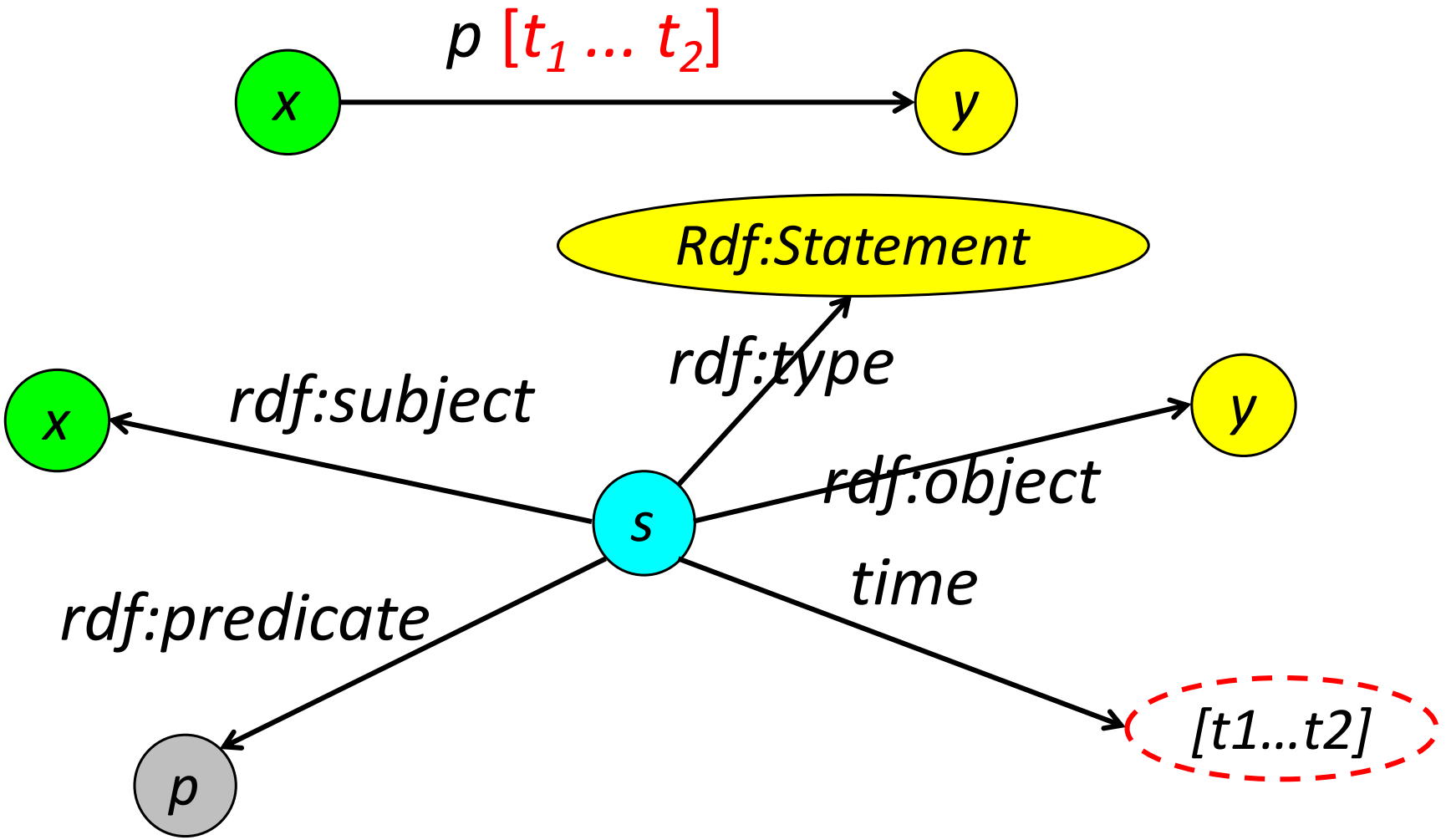
Problem: how to represent



How to implement entailment ?

Reification

transform relations into objects



Discussion

Representation

- complete
- replace 1 triple by $\geq$ 3 triples

Queries become much more complex

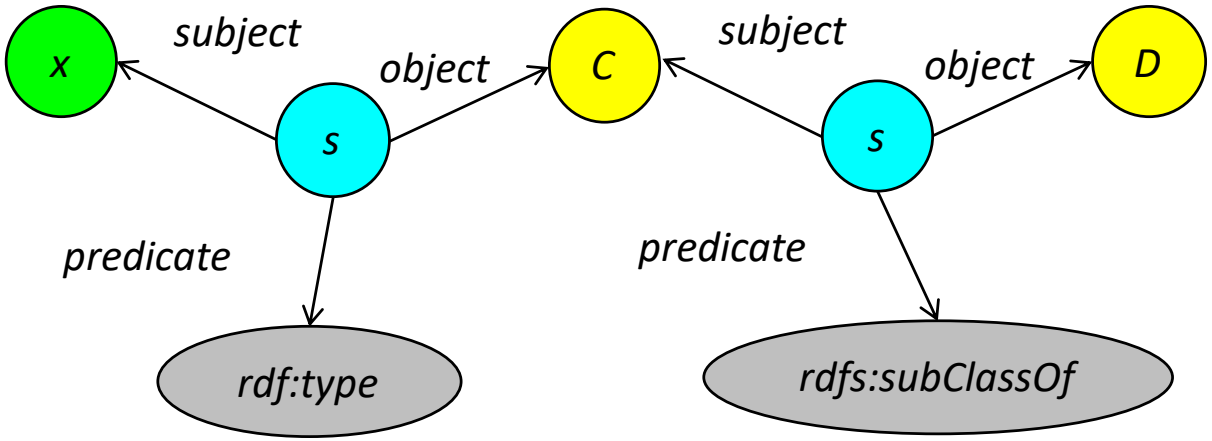
```
select ... where {?x ?p ?y}
```

$\Downarrow$

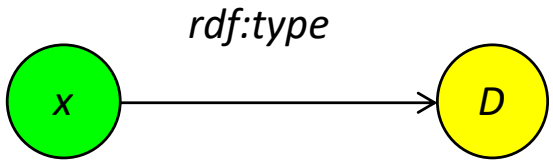
```
select ... where
{?s rdf:subject ?x; rdf:object ?y; rdf:predicate ?p}
```

Discussion

Reification is not taken into account in RDF, RDFS, OWL entailment
$\Rightarrow$ no reasoning on the temporal triples



$\not\Rightarrow$

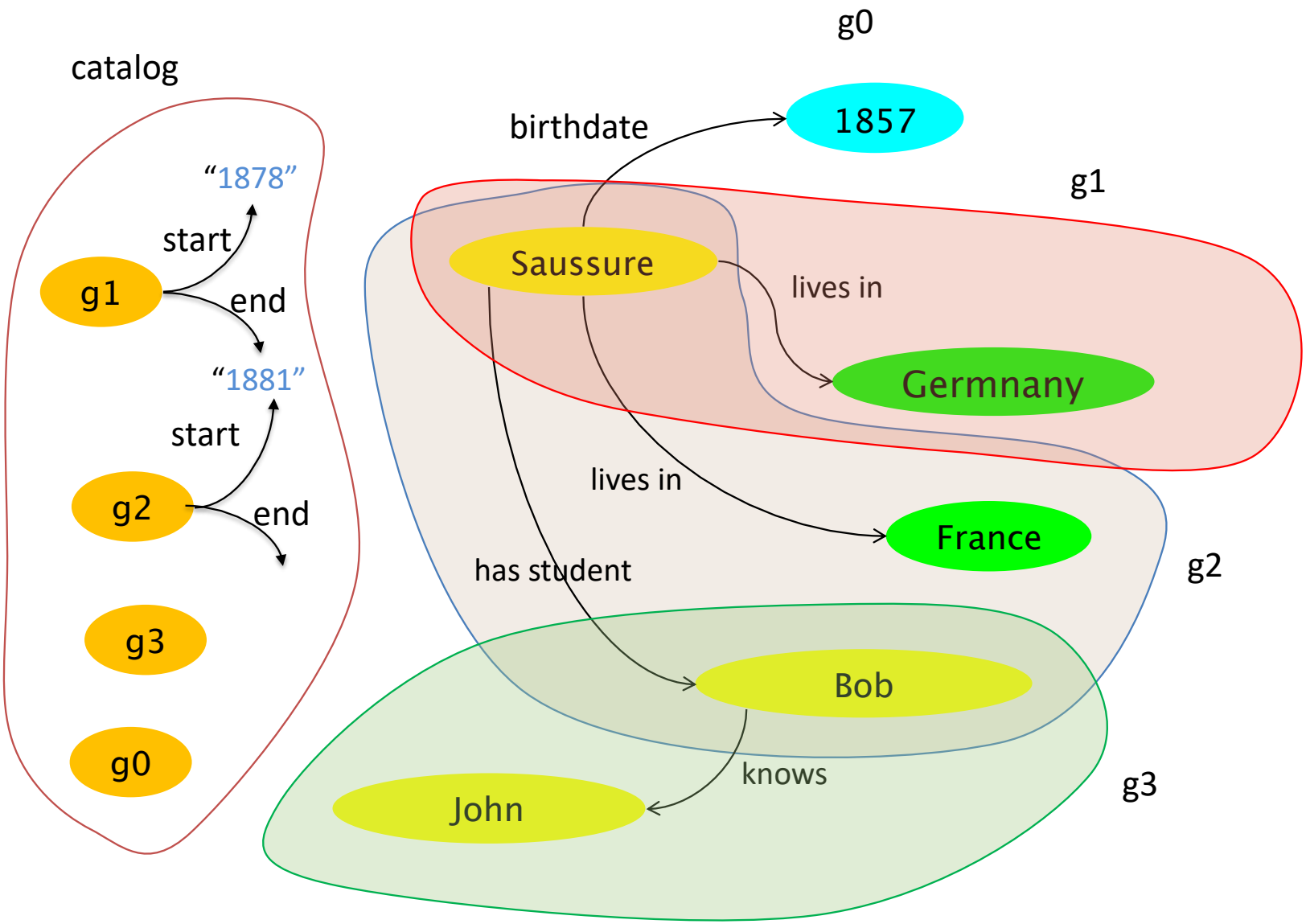


Named graph technique

- Each named graph has an associated time interval and contains triples that are valid for that time interval[1].
- An additional graph is used as a catalog of the named graphs and the interval associated with each.

[1] Tappolet, J. and Bernstein, A., Applied Temporal RDF: Efficient Temporal Querying of RDF Data with SPARQL. In: Proceedings of the European Semantic Web Conference, LNCS 5554, (2009) 308-22

Example


catalog
"1878"
start
g1
end
"1881"
start
g2
end
g3
g0
g0
birthdate
1857
g1
Saussure
lives in
Germnany
lives in
France
g2
has student
Bob
knows
John
g3

```
1  # retrieve validity interval
2  [start, end] = tripleToAdd.validity
3  if tripleToAdd containsOneOrMore blankNode
4          # generate URI for blank-node
5          tripleToAdd = convertBlankToURI(tripleToAdd)
6  endif
7  # if no named graph for the interval exists then make one
8  if !namedGraph[start, end].exists
9    create new namedGraph[start, end]
10   # add the new named graph to directory in default graph
11   namedGraph.defaultGraph += namedGraph[start,end].temporalInfo
12 endif
13 namedGraph[start,end] +=  tripleToAdd
```

Listing 1. Pseudo Code for an insert operation into a temporal graph

```
1 <PREFIX time: http://www.w3.org/2006/time#>
2 <PREFIX foaf: http://xmlns.com/foaf/0.1/#>
3 SELECT  ?s2 ?e2 ?person WHERE{
4         [?s1,?e1] ?einstein foaf:name "Albert Einstein" .
5         [?s2,?e2] time:intervalOverlaps [?s1,?e1] .
6         [?s2,?e2] ?person a foaf:Person .
7 }
```

Listing 4. τ-SPARQL: Interval relations

```
1  <PREFIX time: http://www.w3.org/2006/time#>
2  <PREFIX foaf: http://xmlns.com/foaf/0.1/#>
3  SELECT  ?s2 ?e2 ?person WHERE{
4          GRAPH g1 { ?einstein foaf:name "Albert Einstein" .}
5          ?g2 time:intervalOverlaps ?g1 .
6          GRAPH g2 { ?person a foaf:Person }.
7          ?g2 time:hasBeginning ?start .
8          ?start time:inInteger ?s2 .
9          ?g2 time:hasEnd ?end .
10         ?end time:inInteger ?e2 .
11 }
```

Listing 6. Rewritten τ-SPARQL query

Discussion

- Reduces the number of triples required over some other approaches.
- Problem with blank nodes
  - B-nodes == existentially qualified variables
  - the scope of quantification is the graph
  - this approach puts statements about the same b-node for different time intervals into different named graphs
  - To avoid this problem
    - b-nodes are replaced by URIs thus allowing the use of off the shelf software for processing RDF.
- Named graphs are not part of description logic (not considered in OWL)

4D Fluents

The 4D approach[2] is not something that immediately appeals to common sense, as statements such as

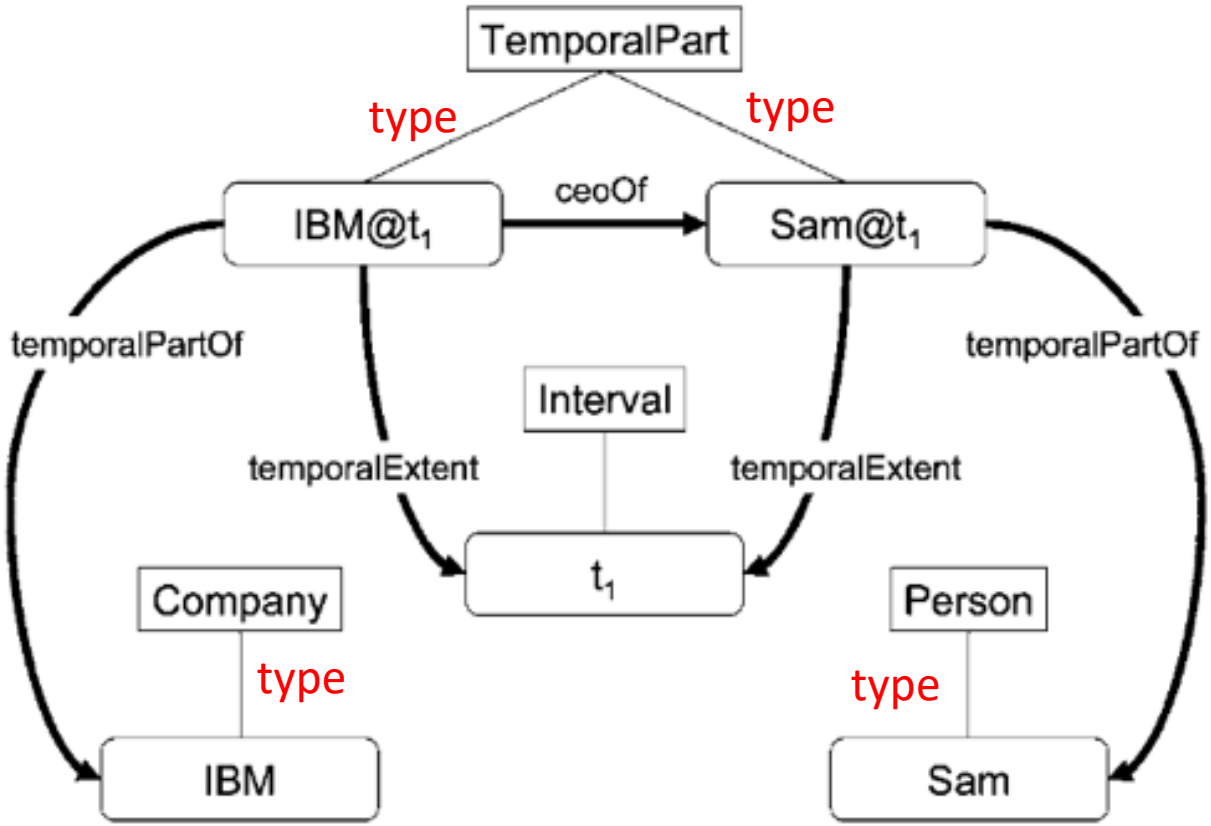
> *"Joe walked into the room"*

must be represented as the logical equivalent of

> *"A temporal part of Joe walked into a temporal part of the room".*

[2] C. Welty and R. Fikes. A Reusable Ontology for Fluents in OWL. In Formal Ontology in Information Systems B. Bennett and C. Fellbaum (Eds.) IOS Press, 2006.

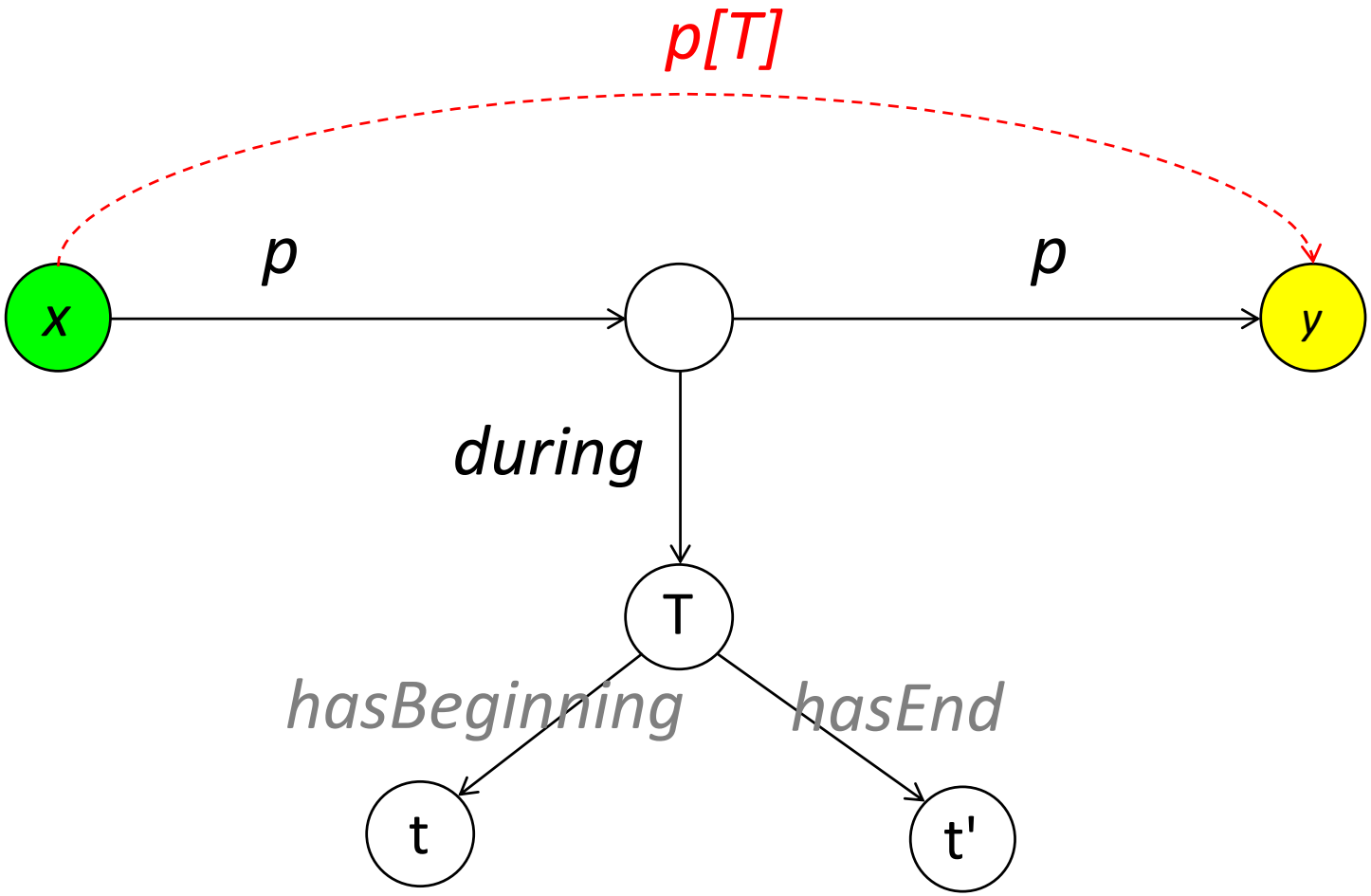
Example


TemporalPart
type
type
IBM@t1
ceoOf
Sam@t1
temporalPartOf
temporalPartOf
Interval
temporalExtent
temporalExtent
t1
Company
type
Person
type
IBM
Sam

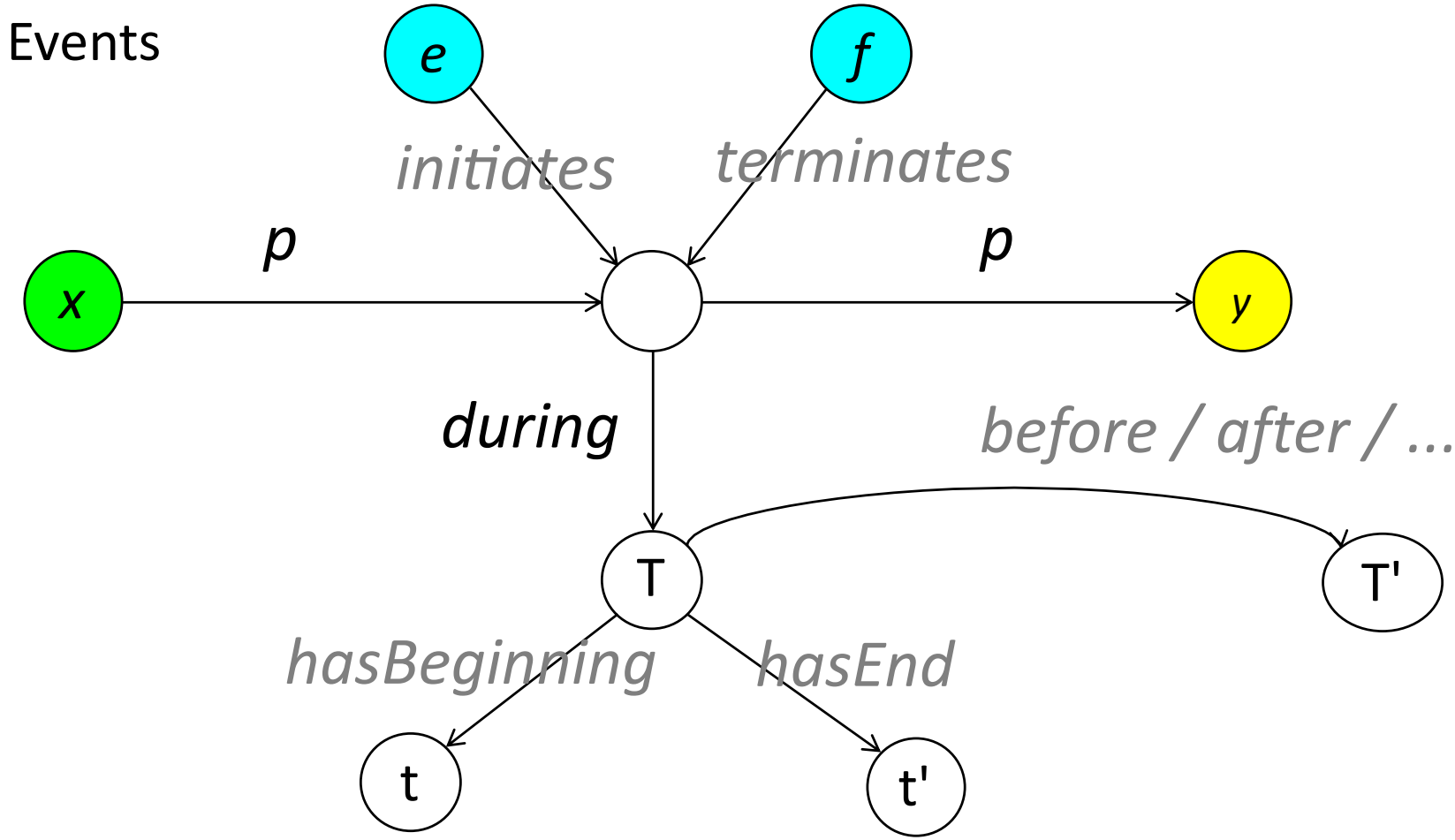
Discussion

- Entirely compatible with RDF and OWL
  - except for synchronic reasoning (impossible to restrict inference to triples that "occur at the same time"
- RDF/S reasoners can be used to infer new facts
- Proliferation of entities
  - each entity is represented by several slices

N-ary relation pattern for fluent relations



With events and temporal relations



Entailment

Non-temportal or basic temporal entailment can be expressed in OWL

$$X \equiv \exists livesIn.(\exists during.(\exists hasBeginning.\{1900\}) \sqcap \exists livesIn.EuropeanCity)$$

More complex inferences must be expressed in SPARQL (SPIN)

Example

Inference rule for a temporally functional property (has only one value at a given instant)

```
insert (?y1 owl:sameAs ?y2)
where {Q(?x, ?f1, ?y1, ?i1),
       Q(?x, ?f2, ?y2, ?i2),
      filter (overlaps(?i1, ?i2))}
```

where

```
Q(?X, ?F, ?Y, ?I)
```

represents

```
?F a FluentRelation. ?X prop ?F. ?F prop ?Y.
?F during ?I.
```

Inference that generate new nodes

Representing the rule:

> *If a manuscript M is a letter from A to B and the writing time of M is [t1 .. t2] then A knows B during [t1 .. end of considered period]*

```
INSERT {?A :knows
  [a :FluentRelation ;
   :during [a :TimeInterval ;
              :hasBeginning ?t1;
              :hasEnd :end-of-period];
   :knows ?B]}
 WHERE {?L a :Letter; :author ?A;
         :to ?B; writingDate ?t1}
```

$\Rightarrow$ creation of a new blank node

Discussion

Compatible with RDFs/OWL entailment, except for synchronic reasoning
Creation of new nodes when infering new temporal facts $\Rightarrow$ potentially infinite computations, unless

- no redundant fluent is created
- the created nodes are never used in a subjet or object position in a new fluent assertion