Modeling and reasoning about geospatial event dynamics using semantic web technologies

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Abstract. A data model that explicitly represents events is an important step towards revealing underlying mechanisms for geographic changes, and facilitating the explanatory and predictive analysis of geographic dynamics. In this paper, we propose a Resource Description Framework (RDF) model for space-time events that integrates spatial, temporal and semantic aspects. A space-time event ontology has been designed that captures the conceptual relations between events and their participants, enhancing the capacity of a semantic reasoning engine to support reasoning about the causal relations among events as well as other semantic properties. A prototype flood event knowledgebase has been developed using Sesame and SWRLAPI. We present a case study using data from a severe flood in Iowa City, IA during 2008, applying the RDF model to analyze the event dynamics caused by river flooding and building closures.

Keywords: RDF, space-time events, semantic web, event-based model

1 Introduction and motivation

Representing and analyzing the dynamics of geographic phenomena (for example, natural hazards [1] and land cover change) is an important step for understanding underlying geographic processes. Research has investigated modeling approaches for representing dynamic geographic phenomena, including a temporal snapshots model [2], temporal sequences of changing objects [3], and event-based models that explicitly represent space-time events that underlie changes [4]–[7]. A data model that explicitly represents events is important for revealing underlying mechanisms for geographic changes, thus facilitating the explanatory and predictive analysis of geographic dynamics that is key to so many geospatial applications. However, traditional data models for space-time events (e.g., an object-oriented model for events) don't necessarily offer full support for spatiotemporal reasoning, and giving insights into why certain changes occur in a geographic domain. In this research, we propose a Resource Description Framework (RDF) model for space-time events that integrates spatial, temporal and semantic aspects of space-time events. Specifically, we propose a model that captures the *thematic roles* of participants in space-time events contributing useful semantic information about events together with their spatiotemporal dimensions. Thematic roles are semantic relations that link event participants with actions [8]. We model space-time events from a combined spatial and temporal perspective, derived from the OGC GeoSPARQL[1] standard and W3C time[2] ontology. A space-time event ontology has been designed that captures relations between events and their participants, and enhances the capacity of semantic reasoning engines to explore and relate events, revealing possibly new insights about potential causes of certain domain events. A prototype flood event knowledgebase has been developed to test these ideas with data from a severe flood in Iowa City, IA during 2008 and using Sesame[3], a Java framework for processing RDF data, and SWRLAPI[4], a Java package with temporal reasoning support.

2 Related work

As an increasing amount of geospatial data are being published on the web, geospatial semantic web research [9] has become a key topic for the GIScience research community. Different semantic web technologies have been adapted for geospatial data, especially as space and time play increasingly important roles on the semantic web [10]. For example, GeoSPARQL defines a vocabulary for representing geospatial data in RDF and an extension to the SPARQL query language for processing geospatial rules and queries. Treatment of events is important for understanding and representing change including the appearance and disappearance of phenomena and other kinds of change in geographic domains. In the GIScience research community, Worboys and Hornsby [4] proposed a geospatial event model by extending a traditional object-oriented approach, and laid the groundwork for treating events as first-class entities in the spatiotemporal modeling process. Li et al. [6] designed an event-driven spatio-temporal data model to model real-time sensor data source. The model is described and realized in UML. Devaraju et al. [7] presented a formal model that use a rule-based mechanism to infer information about events from in-situ observations. Built upon Semantic Sensor Web framework, Llaves et al. [11] presented a Complex Event Processing technique that defines changing situations using event patterns. Event-oriented approaches for geographic phenomena that are based on temporal logic (e.g., event calculus) have been discussed by Worboys [5], and in order to detect causality in spatiotemporal data, algorithms have been developed that search causal rules in logic format from spatiotemporal data [12]. The representation and explanation of change and movement also have a long history in knowledge representation research. Here, participants in actions/events are modeled as playing different thematic roles. Sowa [8] organized these thematic roles into four different categories (i.e., *initiator, resource, goal, essence)*, corresponding to Aristotle's four causes for change and movement. Smith and Grenon proposed a set of formal ontological relations that link SNAP and SPAN entities [15], striving to better integrate spatial and temporal dimen-

1 http://www.opengis.net/ont/geosparql
2 https://www.w3.org/2006/time
3 http://rdf4j.org/
4 https://github.com/protegeproject/swrlapi

sions of real-world entities in ontological models. More recently, Janowicz [13] has used thematic roles to design a new way of measuring semantic similarity between geographic entities, such as theater and sport arena based on thematic roles.

3 Representing space-time events using a semantic web approach

Space-time events are the drivers for changes in geographic domains. From an ontological perspective, space-time events are *occurrents* [14] that are ephemeral, i.e., they happen and then go out of existence (e.g., a traffic jam, a river flood, a wild fire), and can be conceptualized as occupying spatiotemporal regions. Events can also often be identified according to their causes and effects. In our RDF data model, events are modeled by a space-time event class that inherits properties from the *SpatialObject* Class defined in GeoSPARQL ontology and *TemporalEntity* class defined W3C time ontology. Formally, we can define a space-time event in turtle format as:

```
@prefix time:  <http://www.w3.org/2006/time#> .
@prefix geo:   < http://www.opengis.net/ont/geosparql#> .
@prefix rdfs:  <http://www.w3.org/TR/rdf-schema/#> .
@prefix :      <http://st-event.org/#> .
:st_event rdfs:subClassOf geo:SpatialObject .
:st_event rdfs:subClassOf time:TemporalEntity.
```

GeoSPARQL is designed to support representation and queries about geospatial data, including qualitative reasoning about topological relationships between spatial entities (e.g., nine-intersection topological relations). The W3C time ontology defines properties of temporal objects and relations between them (i.e., Allen's temporal interval relation algebra). Since a temporal object can be modeled as either an *time:Instant* or *time:Interval,* we can model events that exist for a duration (e.g., traffic jams), or events that don't have lasting existence (e.g., traffic accidents). By integrating properties of both *geo:SpatialObject* and *time:TemporalEntity*, we can use a semantic web reasoning engine to reason about the spatiotemporal relationships between events. Since a semantic web data model is serialized as triples in an RDF triple store, this provides a consistent framework to integrate spatial, temporal and semantic information about space-time events.

4 Participants of space-time events

Changes to spatial objects (e.g., *creation, alteration, destruction)* only come about with the occurrence of space-time events [4]. When an event occurs, the objects that participate in events can play different *thematic roles*. Thematic roles are conceptual relations that link actions to the participants of occurrents [8]. Following Sowa [8], thematic roles are organized into two general classes, *product and source* (Fig. 1). *Source* can be further classified as *resource* and *initiator* where *initiator* is the agent that starts an event with or without voluntary intention, and *resource* must be present throughout the event, but does not actively control the event (e.g., the instrument being used).

Product can also be further classified as *goal* and *essence* where *goal* is a participant in an event that controls the event from another direction (e.g., recipient). *Essence* refers to an essential participant of an event that represents the byproduct of an event. Essence can be further classified as *Patient and Theme. Patient* represents participants that undergo some structural change as a result of the event, while *theme* represents participants that may be moved but not structurally changed. Take a simple event as an example,

```
[Iowa river] flooded the [Library basement].
```

Iowa River is labeled as the *initiator* of the event, or more precisely, an *effector*. Library basement is the *product* of the event, or an *essence.* To make full use of thematic roles, we can label *library basement* as *patient* since this object might have been structurally changed during this flood. These roles can be further classified based on different kinds of actions. For example, a movement event has participants such as *origin, path, and destination* that play thematic roles.

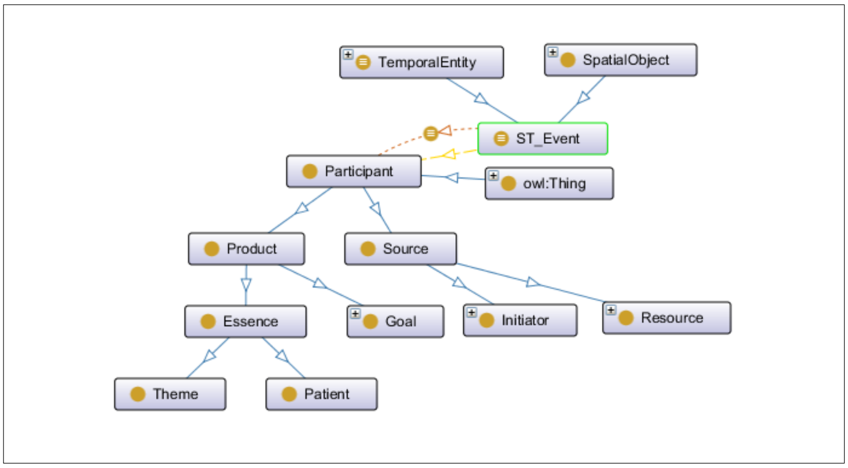

Fig. 1. Part of the classes in space-time event ontology

In our ontology, the object properties that link a space-time event with its participants are hierarchical based on different granularities of thematic roles. For example,

```
:hasEssence rdfs:subPropertyOf :hasProduct
:hasGoal     rdfs:subPropertyOf :hasProduct
:hasInitiator  rdfs:subPropertyOf :hasSource
:hasResource   rdfs:subPropertyOf :hasSource
```

Modeling the thematic roles of space-time event participants can give the semantic reasoning engine the ability to reason about cause and effects in a space-time event triple store. For example, a street is an essential participant or an *essence* for a traffic_jam event as shown below:

```
:traffic_jam1 time:hasBeginning "2015-02-08T17:00:00" .
:traffic_jam1 time:hasEnd "2015-02-08T19:00:00" .
:traffic_jam1  geo:hasExactGeometry [
                geo:asWKT "Polygon(…)"^^geo:wktLiteral ].
:traffic_jam1 :hasEssence :ex_street.
:ex_street     geo:hasExactGeometry [
                geo:asWKT "Polygon(…)"^^geo:wktLiteral ].
```

If there is another event in the knowledgebase, for example a broken water main on the same :ex_street where the traffic jam is happening, we can reason about whether these two events are related based on their spatial, temporal and semantic relations (i.e., the thematic roles of different participants).

5 Prototype development and case study

In this section, we introduce a prototype system that has been implemented using a Sesame framework. While the Sesame framework provides support for RDF data reading, storing, and querying, it does not support temporal reasoning, and so we integrated SWRLAPI to support the temporal predicates in SPARQL. The support for spatial queries is provided via spatial4j[5] and JTS[6].

To illustrate the application of this space-time event data model that uses thematic roles, we model a scenario involving the University of Iowa campus and severe flooding that occurred during the summer of 2008. Campus buildings are stored as spatial objects in an RDF knowledgebase, and the space-time events in the knowledgebase are from memos recorded by Facilities Management at the University of Iowa (e.g., the changing flood stage of the Iowa River, and building closures). During times of flooding, Facilities Management must monitor the flood stage of the Iowa River and have a plan for when to evacuate buildings, and move out building contents if necessary. Each building on campus requires a certain amount of time to move contents either to higher floors in the building or out and to another location before flooding [16]. For example, the Hydraulics Lab, requires two days to move contents out, and based on the date that flooding is estimated to begin, the building will be closed two days before, in order to have enough time to move items out. The following RDF triples describe three space-time events: Iowa River flood stage rise to 644.2 ft *(:river_644_2*), Hydraulics Lab being flooded *(:HydraulicsLab_Flood*), and Hydraulics Lab being closed *(:HydraulicsLab_Close*). The *:river_644_2* event's geometry was computed using a flood simulation algorithm. This geometry is further linked with a spatial object *:Iowa_River* through *:hasTheme* property, meaning :*Iowa_River* is a participant of the *:river_644_2* event and has been impacted. Both

[5] https://github.com/locationtech/spatial4j
[6] https://github.com/metteo/jts

:HydraulicsLab_Flood and :HydraulicsLab_Close events have the same geometry as Hydraulics Lab. :*Iowa_River* has the thematic role of *initiator* (*effector*) of *:HydraulicsLab_Flood* event, while :*Hydraulics_Lab* has the role of *patient* for this event.

```
:river_644_2 geo:hasExactGeometry [
            geo:asWKT "Polygon(-91.567595 41.670548,
      …)"^^geo:wktLiteral ].
:river_644_2 time:hasBeginning  "2008-06-10T06:00:00".
:river_644_2 time:hasEnd  "2008-06-12T08:00:00".
:river_644_2 :hasTheme :Iowa_River.
:HydraulicsLab_Flood time:hasBeginning  "2008-06-
10T06:00:00".
:HydraulicsLab_Flood time:hasEnd  "2008-06-12T08:00:00".
:HydraulicsLab_Flood :hasPatient :Hydraulics_Lab.
:HydraulicsLab_Flood :hasEffector :Iowa_River.
:HydraulicsLab_Close time:hasBeginning  "2008-06-
08T06:00:00".
:HydraulicsLab_Close time:hasEnd  "2008-07-11T08:00:00".
:HydraulicsLab_Close :hasPatient :Hydraulics_Lab.
                      ⋮
```

If we know that the Hydraulics Lab was closed on 06/08/2008, we can reason about the possible causes based on spatiotemporal and semantic relations between *:HydraulicsLab_Close* event and other space-time events, e.g., flood stage changes. The following SPARQL query will retrieve the space-time events that impact the hydraulics lab and that have occurred two days before or after the building closure.

```
Select ?e1 where
{
?e1 time:hasBeginning ?ist1.
?e1 :hasPatient   :Hydraulics_Lab.
:HydraulicsLab_Close time:hasBeginning ?ist2.
FILTER (time:duration(2,?ist1,?ist2,time:day)
|| time:intervalOverlaps(?2,?ist2,ist1,time:day))
}
```

The return for this query is *:HydraulicsLab_Flood* event. It is possible to further investigate or follow the *initiator* of *:HydraulicsLab_Flood* event (i.e., *:Iowa_River*), especially if we are interested in other space-time events that also have :*Iowa_River* as a participant. In addition, a user may want to retrieve space-time events that spatially overlap with *:HydraulicsLab_Flood* (Fig. 2), and share a temporal relation such as *before*, *meets*, *starts* or *overlaps*. This query is expressed as:

```
Select ?e2 where
{
?e2 :hasParticipant   :Iowa_River.
```

```
?e2 geo:hasExactGeometry [ geo:asWKT ?wkte2 ].
:HydraulicsLab_Flood geo:hasExactGeometry [
                    geo:asWKT ?wkthf ].
FILTER (time:before(?e2, :HydraulicsLab_Flood) ||
time:meets(?e2, :HydraulicsLab_Flood)||
time:overlaps(?e2, :HydraulicsLab_Flood)||
time:starts(?e2, :HydraulicsLab_Flood) &&
geo:ehOverlaps(?wkte2,?wkthf))
}
```

This query will retrieve *:river_644_2 event,* i.e., a change in river stage to 644.2 ft. This reasoning involves three space-time events and two (participant) spatial objects. It is possible to infer that the cause of the Hydraulics Lab closure on 06/08/2008 is that Iowa River flood stage was predicted to rise to 644.2 ft on 06/10/2008, a flood stage with dangerous water levels for the Lab. If we want to query further and find out what may be the cause for the Iowa River flood stage rising to this predicted height, we can link to other knowledgebases (e.g., river gauge sensor data, precipitation data), and in this way, we can reason about a wide range of geospatial event dynamics for this time period.

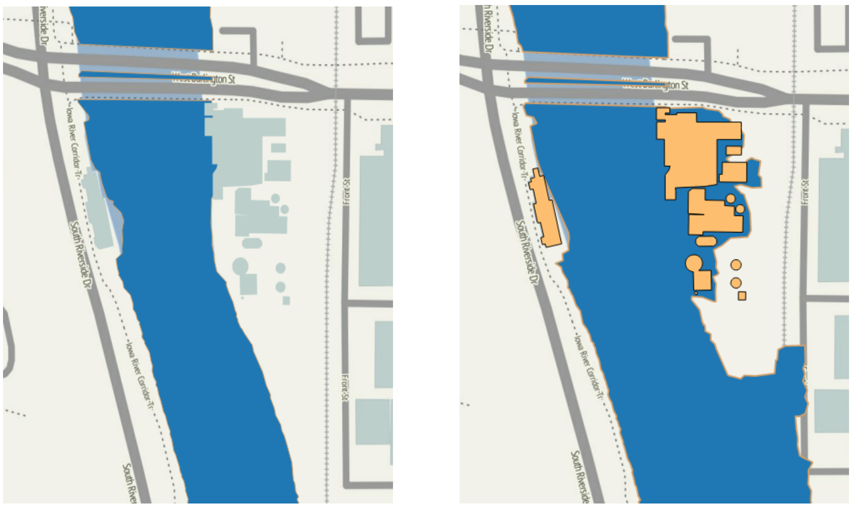

Fig. 2. Geo-visualization of space-time events. River flood stage increasing to 639.2ft (left blue) and again to 644.2ft (right blue). Hydrologic Lab and Power Plant flooded (right orange).

6 Conclusions and discussion

In this research, we designed a RDF model for space-time events, supported by a domain ontology that integrates spatial, temporal and semantic relations. The integration of thematic roles and spatiotemporal reasoning can be useful for capturing causal factors behind certain geographic changes, and understanding the underlying processes. The reasoning capacity of semantic web engines for space-time events can be enhanced beyond spatiotemporal reasoning through the use of thematic roles. If domain rules are incorporated into an event knowledgebase, it becomes possible to make predictive analysis based on real-time event information (e.g., wireless sensor data). In this research, labeling the thematic roles of participants in a space-time event is the one of the key challenges. Active research is still ongoing in a number of communities, e.g., natural language processing [17], regarding methods for automatically labeling the thematic roles of participants. This will be helpful for GIScientists interested in using thematic roles, as assigning thematic roles to participants in space-time events may not be so clear-cut in some cases.

7 References

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