Linear Constraint Databases for the Semantic Web:

The Model stRDF and the Query Language stSPARQL

Manolis Koubarakis

Kostis Kyzirakos

Manos Karpathiotakis

Dept. of Informatics and Telecommunications

National and Kapodistrian University of Athens

Talk Outline

- Motivation
- The Data Model stRDF
- The Query Language stSPARQL
- Implementation
- Future Work

Motivation

How do we represent spatial and temporal metadata in the Semantic Web?

Example:

- The vision of the **Semantic Sensor Web**: annotate sensor data and services to enable discovery, integration, interoperability etc. (Sheth et al. 2008, SemsorGrid4Env)
- Sensor annotations involve **thematic, spatial** and **temporal metadata.** Examples:
  - The sensor measures temperature. (thematic)
  - The sensor is located in the location represented by point (A, B). (spatial)
  - The sensor measured -3^0 Celsius on 26/01/2010 at 03:00pm. (temporal)

Motivation (cont'd)

Example:

- The vision of the **Geospatial Semantic Web**: Provide a formal semantic specification to enable the discovery, query and consumption of geospatial content.

How about using RDF?

Good idea. But **RDF can represent only thematic metadata** properly. What can we do about spatial and temporal metadata?

Previous Work

- Time in RDF (Gutierrez and colleagues, 2005).
- SPARQL-ST (Perry, 2008).
- SPAUK (Kollas, 2007)
- ...

Our Approach

- Use ideas from **constraint databases** (Kanellakis, Kuper and Revesz, 1991).
  Slogan: What's in a tuple? Constraints.
- Extend RDF to a constraint database model.
  Slogan: What's in a triple? Constraints.
- Extend SPARQL to a constraint query language.
- Follow exactly the approach of CSQL (Kuper et al., 1998).
  - Nested relational model with **one level of nesting to represent point sets.**
  - Use **linear constraints** to encode these point sets (that are used to represent spatial and temporal objects).

Spatial Metadata Using Constraints

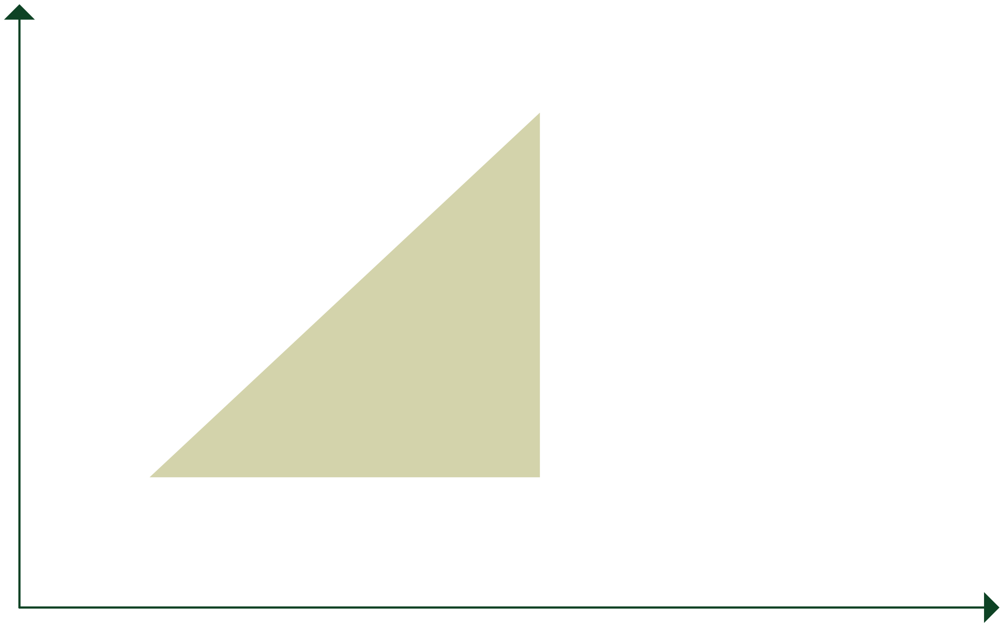
- We start with a FO language $\mathcal{L} = \{\leq, +\} \cup \mathbb{Q}$ over the structure $\mathcal{Q} = \langle \mathbb{Q}, \leq, +, (q)_{q \in \mathbb{Q}} \rangle$.
- **Atomic formulae:** linear equations and inequalities of the form

$$(\sum_{i=1}^{p} a_i x_i) \Theta a_0$$

where Θ is one of $=$, $\leq$ or $<$.

- **Semi-linear point sets**: sets that can be defined by quantifier-free formulas of $\mathcal{L}$.

Example

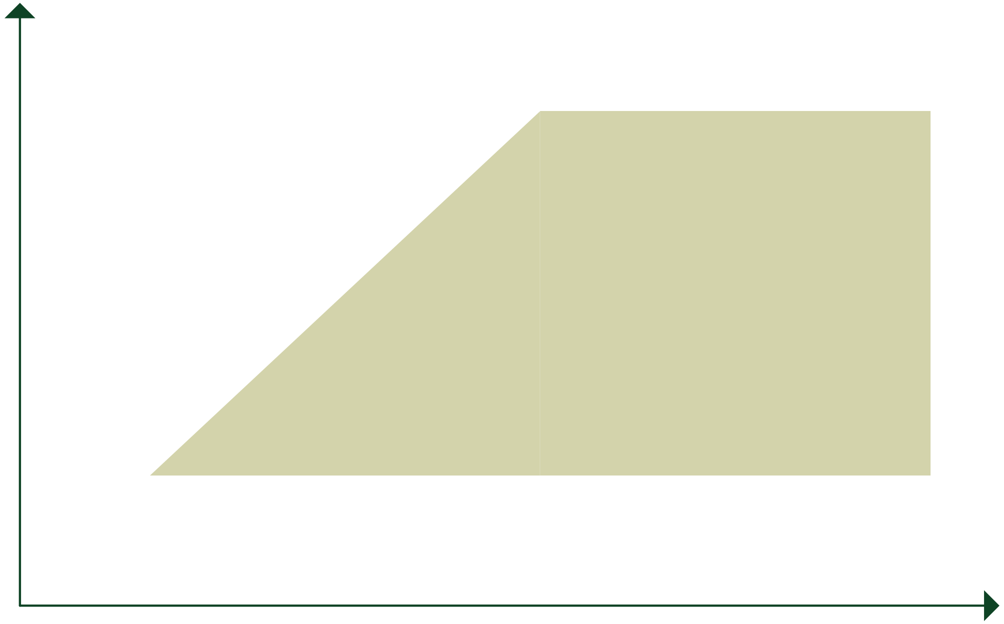


$$x <= 8 \wedge y >= 2 \wedge y <= x$$

Example

$$8 \leq x \leq 14 \land 2 \leq y \leq 8$$

Example



$$(x <= 8 \wedge y >= 2 \wedge y <= x) \vee (8 \leq x \leq 14 \wedge 2 \leq y \leq 8)$$

The sRDF data model

- Let I, B and L be the sets of IRIs, blank nodes and literals.
- Let C_k be the set of quantifier-free formulae of $\mathcal{L}$ with k free variables ($k = 1, 2, \ldots$).
- Let C be the infinite union $C_1 \cup C_2 \cup \cdots$.
- An **sRDF triple** is an element of the set $(I \cup B) \times I \times (I \cup B \cup L \cup C)$.
- An **sRDF graph** is a set of sRDF triples.
- sRDF can be realized as an extension of RDF with a new kind of **typed literals**: quantifier-free formulae with linear constraints. The datatype of these literals is `strdf:SemiLinearPointSet`.

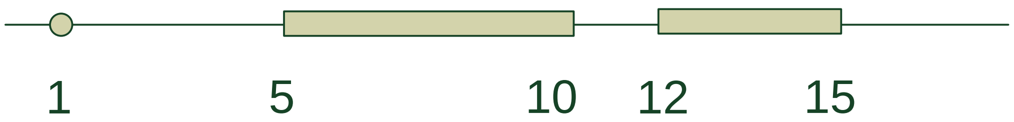
Example of sRDF graph

```
ex:s1 rdf:type ex:Sensor .
ex:s1 ex:has_location "x=40 and y=15"^^strdf:SemiLinearPointSet .
```

Temporal Metadata Using Constraints

- **Time structure**: the set of rational numbers $\mathbb{Q}$ (i.e., time is assumed to be linear, dense and unbounded).
- Temporal constraints are expressed by quantifier-free formulas of the language $\mathcal{L}$ defined earlier, but their syntax is limited to elements of the set C_1.
- **Atomic temporal constraints**: formulas of $\mathcal{L}$ of the following form: $x \sim c$, where x is a variable, c is a rational number and $\sim$ is $<, \leq, \geq, >, =$ or $\neq$.
- **Temporal constraints**: Boolean combinations of atomic temporal constraints using a single variable.

Example



$$t = 1 \vee (t \geq 5 \wedge t \leq 10) \vee (t \geq 12 \wedge t \leq 15)$$

The stRDF data model

stRDF extends sRDF with the ability to represent the **valid time** of a triple:

- An **stRDF quad** (a, b, c, τ) is an sRDF triple (a, b, c) with a fourth component τ which is a temporal constraint.
- An **stRDF graph** is a set of sRDF triples and stRDF quads.

Example of stRDF graph

```
ex:obs1Result om:uom ex:Celcius .
ex:obs1Result om:value "27"
                  "10 <= t <= 11"^^strdf:SemiLinearPointSet .
```

The Query Language stSPARQL

- Syntactic extension of SPARQL
- Formal semantics
  - Closure
- Efficient implementation

Example - Dataset I

Sensor metadata using the SSN ontology:

```
ex:sensor1 rdf:type ssn:Sensor .
ex:sensor1 ssn:measures ex:temperature .
ex:temperature rdf:type ssn:PhysicalQuality .
ex:sensor1 ssn:supports ex:grounding1 .
ex:grounding1 rdf:type ssn:SensorGrounding .
ex:grounding1 ssn:hasLocation ex:location1 .
ex:location1 rdf:type ssn:Location .
ex:location1 strdf:hasGeometry
                    "x=40 and y=15"^^strdf:SemiLinearPointSet .
ex:sensor2 rdf:type ssn:Sensor .
```

Queries - Dataset I

Spatial selection. Find the URIs of the sensors that are inside the rectangle R(0, 0, 100, 100)?

```
select  ?S
where { ?S rdf:type ssn:Sensor .
        ?G rdf:type ssn:SensorGrounding .
        ?L rdf:type ssn:Location .
        ?S ssn:supports ?G .
        ?G ssn:haslocation ?L .
        ?L strdf:hasGeometry ?GEO .
        filter(?GEO inside "0<=x<=100 and 0<=y<=100") }
```

Answer

?S
`ex:sensor1`

Queries - Dataset I

Spatial selection with OPTIONAL. Find the URIs of the sensors that optionally has a grounding that has a location which is inside the rectangle R(0, 0, 100, 100)?

```
select  ?S ?GEO
where { ?S rdf:type ssn:Sensor .
        optional {
               ?G rdf:type ssn:SensorGrounding .
               ?L rdf:type ssn:Location .
               ?S ssn:supports ?G .
               ?G ssn:haslocation ?L .
               ?L strdf:hasGeometry ?GEO .
               filter(?GEO inside "0<=x<=100 and 0<=y<=100") } }
```

Answer

?S	?GEO
ex:sensor1	"x=40 and y=15"^^strdf:SemiLinearPointSet
ex:sensor2	

Example - Dataset II

Sensor observation metadata using the O&M ontology:

```
ex:sensor1 rdf:type ex:TemperatureSensor .
ex:TemperatureSensor rdfs:subClassOf om:Sensor .
ex:obs1 rdf:type om:Observation .
ex:obs1 om:procedure ex:sensor1 .
ex:obs1 om:observedProperty ex:temperature .
ex:temperature rdf:type om:Property .
ex:obs1 om:observationLocation ex:obslocation1 .
ex:obslocation1 rdf:type om:Location .
ex:obslocation1 strdf:hasGeometry
                    "x=40 and y=15"^^strdf:SemiLinearPointSet .
ex:obs11 om:result ex:obs1Result .
ex:obs1Result rdf:type om:ResultData .
ex:obs1Result om:uom ex:Celcius .
ex:obs1Result om:value "27"
                    "(10 <= t <= 11)"^^strdf:SemiLinearPointSet .
```

Example - Dataset II (cont'd)

Metadata about geographical areas:

```
ex:area1 rdf:type ex:RuralArea .
ex:area1 ex:hasName "Brovallen" .
ex:area1 strdf:hasGeometry
           "(-x+1.363636y<-5.272576 and y<79 and -y<-13 and
              x-0.090909y<131.818133) or (y<13 and x<133 and
             -x-1.5y<-128.5)"^^strdf:SemiLinearPointSet .
```

Queries - Dataset II

Spatial and temporal selection. Find the values of all observations that were valid at time 11 and the rural area they refer to.

```
select  ?V ?RA
where { ?OBS rdf:type om:Observation .
        ?LOC rdf:type om:Location .
        ?R rdf:type om:ResultData .
        ?RA rdf:type ex:RuralArea .
        ?OBS om:observationLocation ?LOC .
        ?LOC strdf:hasGeometry ?OBSLOC .
        ?OBS om:result ?R .
        ?R om:value ?V ?T .
        ?RA strdf:hasGeometry ?RAGEO .
        filter(?T contains "t = 11" && ?RAGEO contains ?OBSLOC) }
```

Answer

?V	?RA
"27"	ex:area1

Example - Dataset III

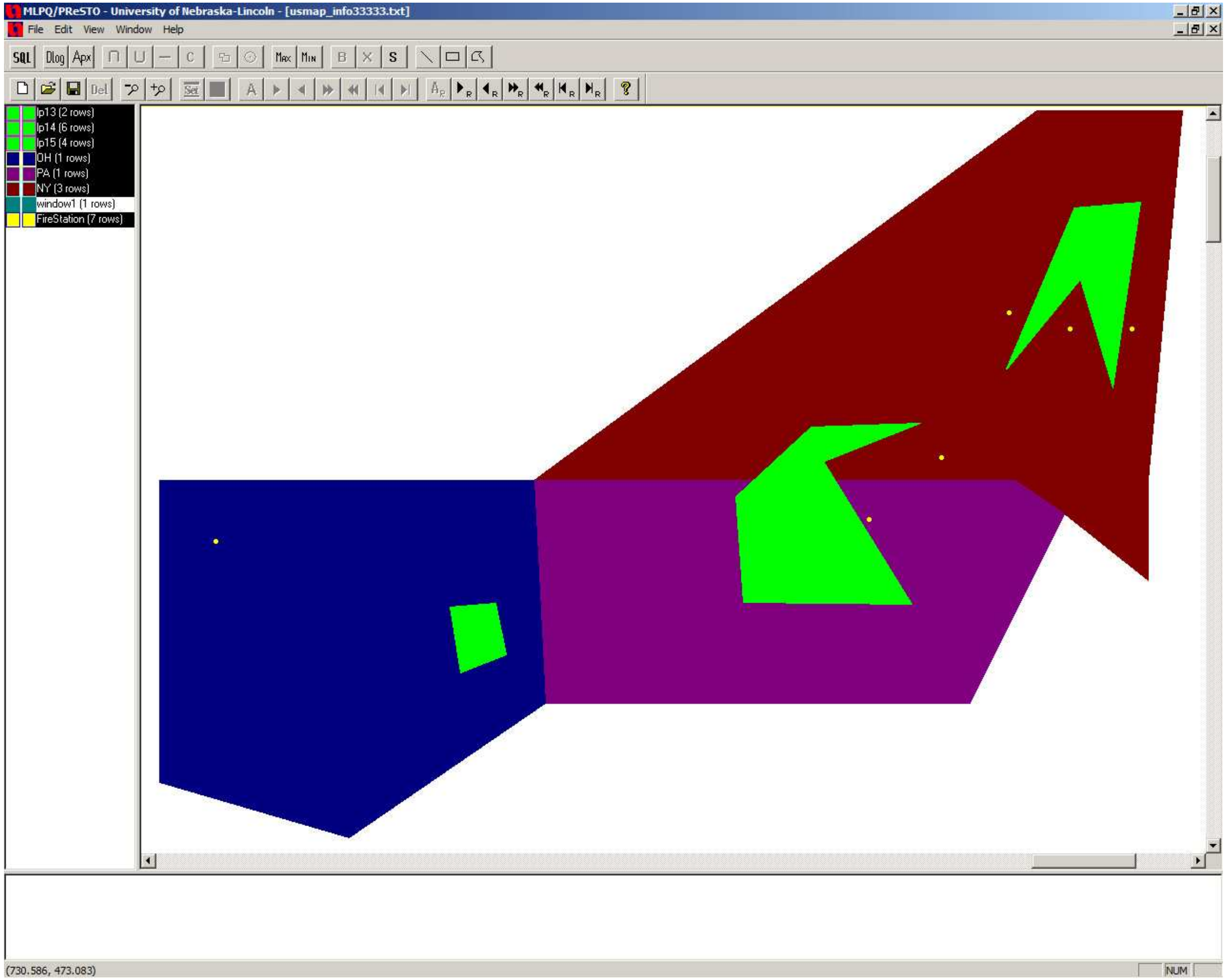
Dataset from a typical GIS application:

```
ex:s1 rdf:type ex:State .
ex:s1 ex:has_name "New York" .
ex:s1 ex:has_geometry "(-66x+90y<-8748 and 26y<12974
      and 110y>47630 and -66x+6y>-52380) or (24y<10392
      and -6x+15y>1497 and 6x+9y>8751) or (-6x+15y <1497
      and 18x<14994 and 12x+15y>16221)"^^strdf:SemiLinearPointSet .

ex:lp13 rdf:type ex:LandParcel .
ex:lp13 ex:land_use "forest" .
ex:lp13 ex:has_geometry
        "x+0.2y<=798 and x-2.5y<=-286 and -x-0.156864y<=-772
         and -x+11.6y<=4078"^^strdf:SemiLinearPointSet .

ex:fs1 rdf:type ex:FireStaton .
ex:fs1 ex:has_location "x=796 and y=437"^^strdf:SemiLinearPointSet .
```

Example - Dataset III (cont'd)



Queries - Dataset III

Query with intersection of areas and spatial function application.
Find all land parcels that are forests and intersect the state of New York; compute the area of this intersection.

```
select ?LP, AREA(?GEO1 INTER ?GEO2) AS ?LPAREA
where {?LP rdf:type  ex:LandParcel .
       ?LP ex:has_use "forest" .
       ?LP ex:has_geometry ?GEO1
       ?S rdf:type ex:State .
       ?S ex:has_name "New York".
       ?S ex:has_geometry ?GEO2 .
       filter(?GEO1 overlap ?GEO2) }
```

Answer

?LP	**?LPAREA**
`"ex:lp13"`	`88.625366`
`"ex:lp15"`	`644.926392`

Queries - Dataset III

Projection and spatial function application. Find the URIs of the fire stations that are north of the state of Pennsylvania.

```
select ?FS
where {?FS rdf:type ex:FireStation .
       ?FS ex:has_location ?FS_LOC .
       ?S rdf:type ex:State .
       ?S ex:has_name "Pennsylvania".
       ?S ex:has_geometry ?GEO .
       filter(MAX(?GEO[2]) < MIN(?FS_LOC[2])) }}
```

Answer

?FS
"ex:fs1"
"ex:fs4"
"ex:fs5"
"ex:fs6"

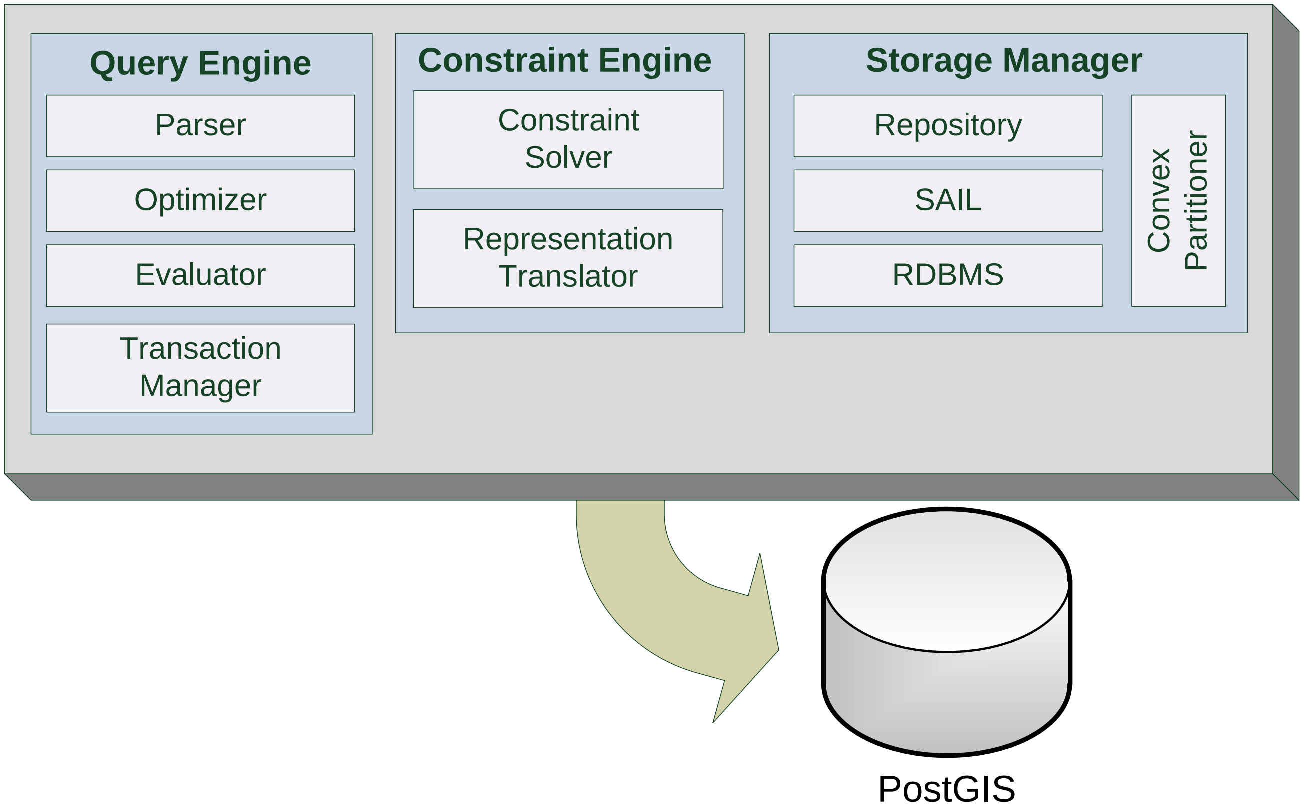
What Else is There in stSPARQL Syntax?

- k-ary spatial terms
  - quantifier-free formulas
  - spatial variables
  - intersection, union, difference, boundary, buffer, minimum bounding box of k-ary spatial terms
  - projections of k-ary spatial terms
- Metric spatial terms
  - VOL, AREA, LEN, MAX, MIN
- Selection predicates
  - Spatial predicates (topological): DISJOINT, TOUCH, EQUALS, INSIDE, COVEREDBY, CONTAINS, COVERS, OVERLAPBDDISJOINT or OVERLAPBDINTER
  - Temporal predicates: BEFORE, EQUAL, MEETS, OVERLAPS, DURING, STARTS, FINISHES
  - a linear equation or inequality of $\mathcal{L}$ with metric spatial terms in the place of variables
- Construction of new spatial terms
  - intersection/union/difference/projection of spatial terms

stSPARQL Semantics

- Extension of the SPARQL semantics of (Perez et al., 2006).
  - Extend the concept of mapping.
  - The semantics of AND, OPT, UNION remain the same.
  - We need to define carefully the evaluation of spatial terms and the semantics of spatial and temporal filters.

The System Strabon



Future Work

- Complete the implementation (see demo for what works now).
- Incomplete information (use the blank nodes for a bit more than what they are currently used).
- OWL 2 and constraints?
- Show that similar extension to RDF and SPARQL could be done for OGC datatypes (instead of constraints).

Thank you!

Backup slides

What if you don't like constraints?

- Introduce datatypes like `Point`, `Line`, `Polygon` etc. and specify them using XML Schema.
- Introduce the appropriate operators in SPARQL e.g., introduce an operator `@` to check whether a geometry is completely contained by another geometry.
- Semantics?

What if you don't like constraints? (cont'd)

Then one could describe a sensor with the following triples:

```
ex:located_at rdfs:range georss:Point .
ex:sensor1 rdf:type ex:Sensor .
ex:sensor1 ex:located_at "5 5"^^georss:Point .
```

Then one could write a window query that asks for all the sensors that are located inside the rectangle R(0, 0, 10, 10) as follows:

```
select  ?sensor
where { ?sensor rdf:type ex:Sensor .
        ?sensor ex:located_at ?sensor_loc .
        filter(?sensor_loc @ "0 0 10 10"^^georss:Box) }
```

Query from the GSW-IE

SeRQL query

```
SELECT airport, city
FROM {airport} rdf:type {c5:C5CapableAirport};
               filter:satisfiesFilter {filter},
     {filter}  rdf:type {filter:DWithin};
               filter:referenceGeometry {city};
               filter:radius {50000"^^xsd:int},
     {city}    rdf:type {cities:City};
               filter:satisfiesFilter {cityFilter},
     {cityFilter} rdf:type {filter:PropertyIsLike};
                  filter:property {"NAME"};
                  filter:literal {"Saint Louis"}
```

Query from the GSW-IE (cont'd)

stSPARQL query

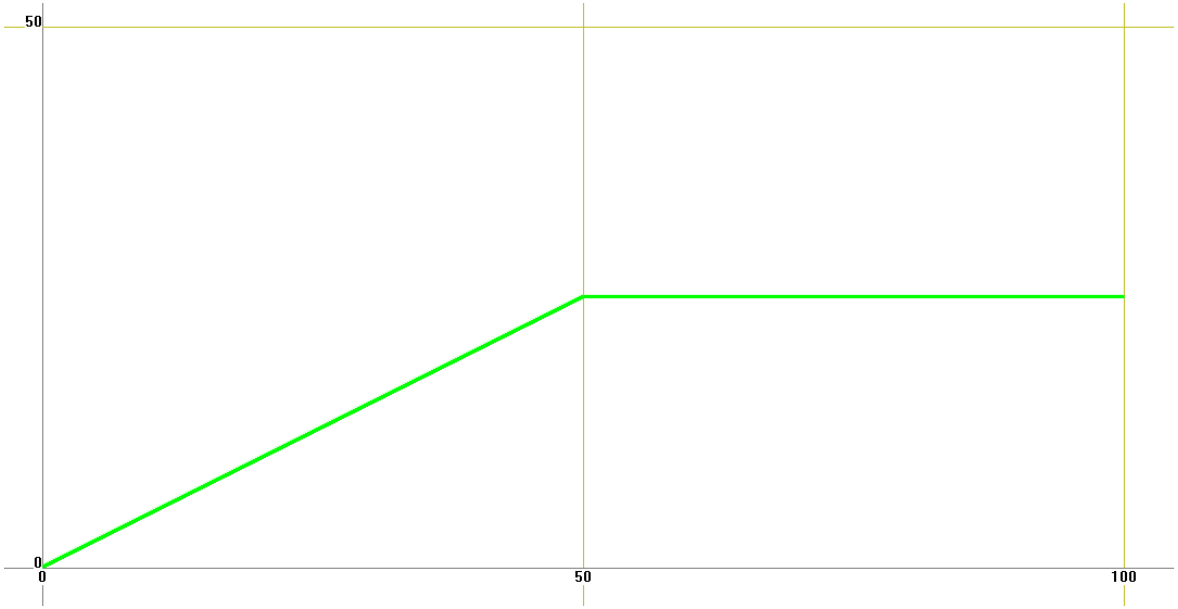
```
SELECT ?airport ?city
WHERE {
   ?airport rdf:type c5:C5CapableAirport;
   ?airport ex:hasGeometry ?airportGEO .
   ?city    rdf:type cities:City;
            ex:hasName ?cityName;
            ex:hasGeometry ?cityGEO .
   FILTER (?cityName LIKE "Saint Louis" &&
           BUFFER(?cityGEO, 5000) containts ?aiportGEO) }
```

Example - Dataset III

Moving sensor metadata using the SSN ontology:

```
ex:sensor2 rdf:type ssn:Sensor .
ex:sensor2 ssn:measures ex:temperature .
ex:sensor2 ssn:supports ex:grounding2 .
ex:grounding2 rdf:type ssn:SensorGrounding .
ex:grounding2 ssn:hasLocation ex:location2 .
ex:location2 rdf:type ssn:Location .
```

Example - Dataset III (cont'd)




```
ex:location2 strdf:hasTrajectory
             "(x=10t and y=5t and 0<=t<=5) or
              (x=10t and y=25 and 5<=t<=10)"^^strdf:SemiLinearPointSet.
```

Example - Dataset III (cont'd)

Metadata about geographical areas:

```
ex:area1 rdf:type ex:RuralArea .
ex:area1 ex:hasName "Brovallen" .
ex:area1 strdf:hasGeometry
           "(-x+1.363636y<-5.272576 and y<79 and -y<-13 and
              x-0.090909y<131.818133) or (y<13 and x<133 and
             -x-1.5y<-128.5)"^^strdf:SemiLinearPointSet .
```

Queries - Dataset III

Intersection of an area with a trajectory. Which areas of Brovallen were sensed by a moving sensor and when?

```
select  (?TR[1,2] INTER ?GEO) as ?SENSEDAREA  ?TR[3] as ?T1
where { ?SN rdf:type ssn:Sensor .
        ?Y rdf:type ssn:Location .
        ?X rdf:type  ssn:SensorGrounding .
        ?RA rdf:type ex:RuralArea .
        ?SN ssn:supports ?X .
        ?X ssn:hasLocation ?Y .
        ?Y strdf:hasTrajectory ?TR .
        ?RA ex:hasName "Brovallen" .
        ?RA strdf:hasGeometry ?GEO .
        filter(?TR[1,2] overlap ?GEO) }
```

Answer

?SENSEDAREA	?T1
"((y=0.5x and 0<=x<=50) or (x=50 and 25<=y<=50)) and ((y<79 and -y<-13 and -x+1.363636y<-5.272576 and x-0.090909y<131.818133) or (y<13 and x<133 and -x-1.5y<-128.5))" ^^strdf:SemiLinearPointSet	"0 <= t <= 10" ^^strdf:SemiLinearPointSet.

One More Query

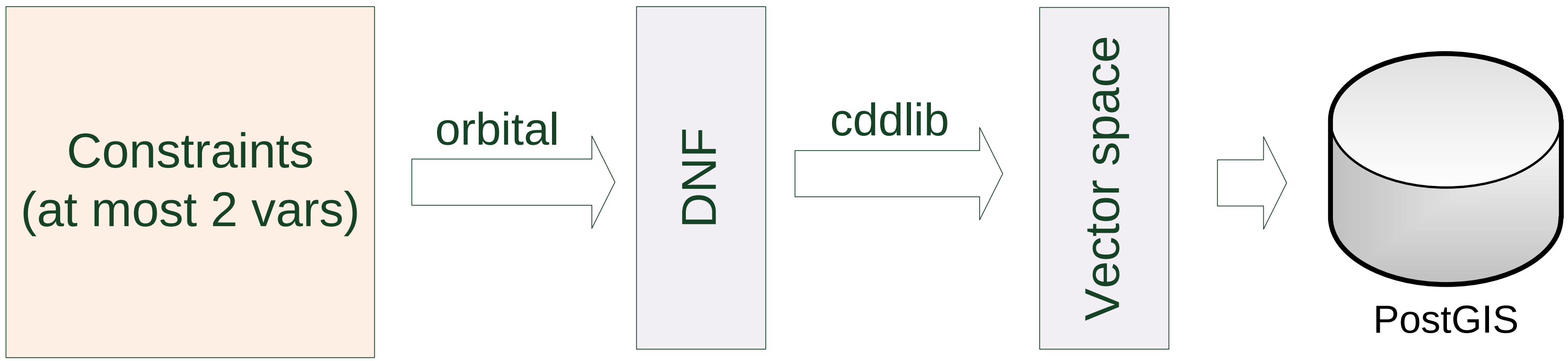
Projection and spatial function application. Find the URIs of the sensors that are north of Brovallen.

```
select   ?SN
where  { ?SN rdf:type ssn:Sensor .
         ?X rdf:type ssn:SensorGrounding .
         ?RA rdf:type ex:RuralArea .
         ?SN ssn:supports ?X .
         ?X ssn:hasLocation ?Y .
         ?Y strdf:hasGeometry ?SN_LOC .
         ?RA ex:hasName "Brovallen".
         ?RA strdf:hasGeometry ?GEO .
         filter(MAX(?GEO[2])<MIN(?SN_LOC[2])) }
```

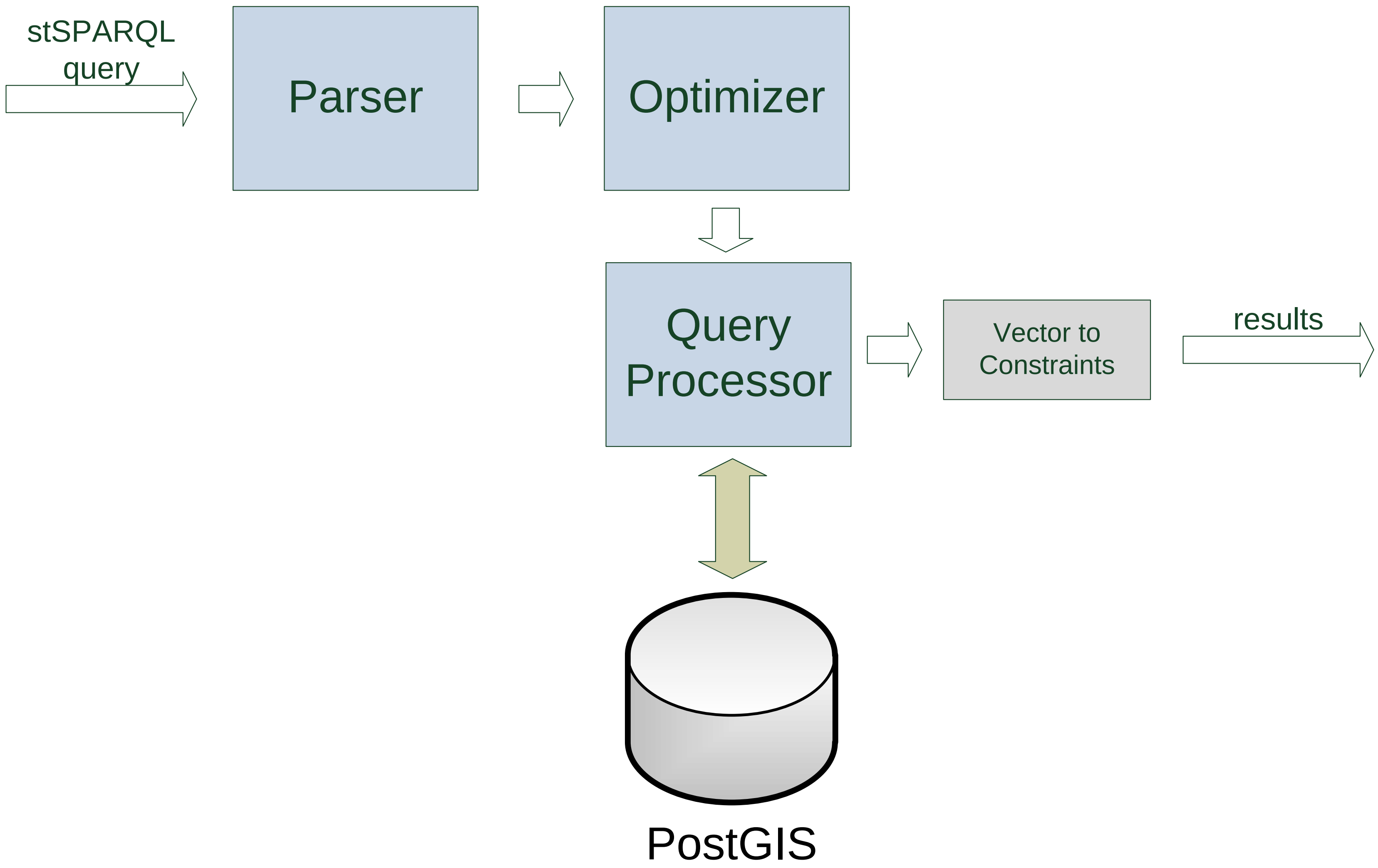
Answer

?SN

Implementation Details: Store



Implementation Details: Query



Strabon in SemsorGrid4Env