The Data Model stRDF and the Query Language stSPARQL

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Outline

Motivation

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^o Celsius on 27/01/2011 at 23:00. (temporal)

How about using RDF?

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

Answer: Extend RDF to represent spatial and temporal metadata.

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.

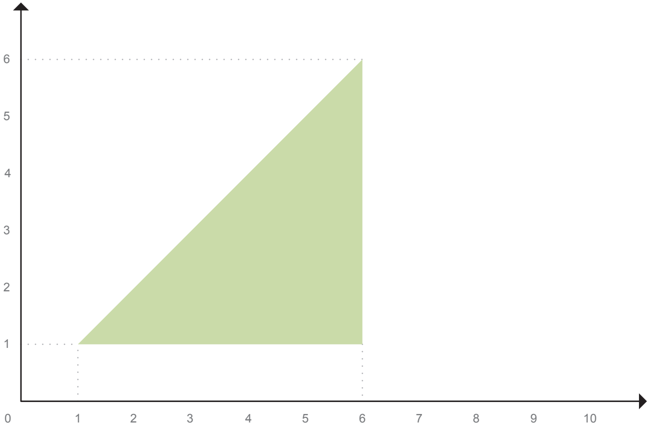
- Extend SPARQL to a constraint query language.

Our Approach - More Details

- 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).

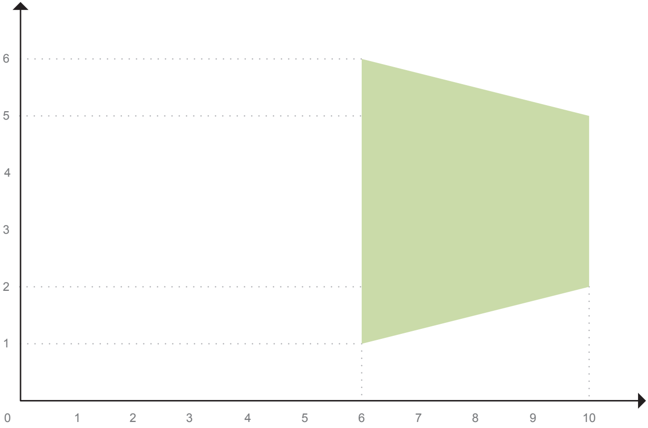
- Follow the approach of Gutierrez et al., 2005, for temporal metadata, but use **linear constraints to represent temporal intervals**.

Spatial Metadata Using Linear Constraints - Example



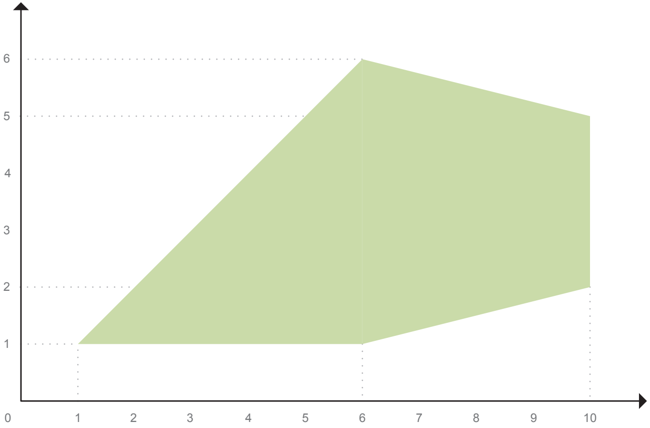
$$x <= 6 \wedge y >= 1 \wedge y <= x$$

Spatial Metadata Using Linear Constraints - Example



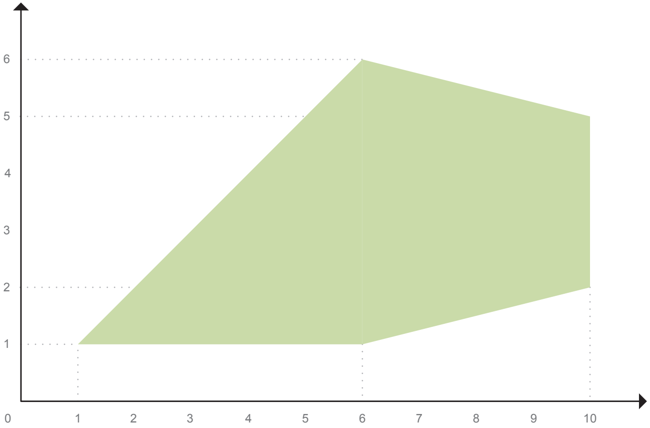
$$x \geq 6 \wedge x \leq 10 \wedge x - 4y \leq 2 \wedge x + 4y \leq 18$$

Spatial Metadata Using Linear Constraints - Example



$$(x <= 6 \wedge y >= 1 \wedge y <= x) \vee (x \geq 6 \wedge x \leq 10 \wedge x - 4y \leq 2 \wedge x + 4y \leq 18)$$

Spatial Metadata Using Well Known Text - Example




```
POLYGON((1 1, 6 1, 10 2, 10 5, 6 6, 1 1))
```

Spatial Metadata Using Linear Constraints - Definitions

- 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 $<$.

- Geometric objects are represented by **semi-linear point sets**: sets that can be defined by **quantifier-free formulas** of $\mathcal{L}$.

Outline

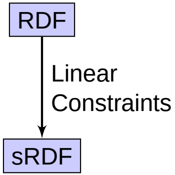
From RDF to sRDF - Example

```
ex:sensor1 rdf:type ex:Sensor .
ex:sensor1 ex:measures ex:Temperature .
ex:sensor1 ex:hasLocation ex:location1 .
```

RDF

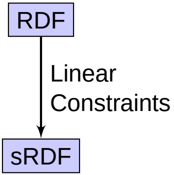
From RDF to sRDF - Example

```
ex:sensor1 rdf:type ex:Sensor .
ex:sensor1 ex:measures ex:Temperature .
ex:sensor1 ex:hasLocation ex:location1 .

  ex:location1 strdf:hasGeometry
    "x=40 and y=15"^^strdf:SemiLinearPointSet .
```



From RDF to sRDF - Example

```
ex:sensor1 rdf:type ex:Sensor .
ex:sensor1 ex:measures ex:Temperature .
ex:sensor1 ex:hasLocation ex:location1 .

  ex:location1 strdf:hasGeometry
   "POINT(40 15)"^^ogc:WKT .
```



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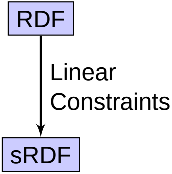
```

New kind of typed literals



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 $C_1 \cup C_2 \cup \cdots$.

Definition

- 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`.

Temporal Metadata Using Constraints - Example

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

Temporal Metadata Using Constraints - Definitions

- **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.

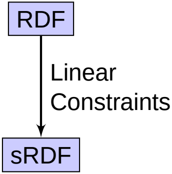
Definition

- **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.

From RDF to sRDF to stRDF - Example

```
ex:sensor1 rdf:type ex:Sensor .
ex:sensor1 ex:measures ex:Temperature .
ex:sensor1 ex:hasLocation ex:location1 .

ex:location1 strdf:hasGeometry
      "x=40 and y=15"^^strdf:SemiLinearPointSet .
```

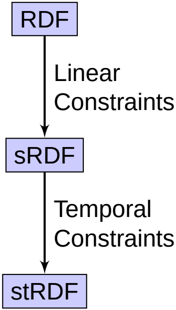


From RDF to sRDF to stRDF - Example

```
ex:sensor1 rdf:type ex:Sensor .
ex:sensor1 ex:measures ex:Temperature .
ex:sensor1 ex:hasLocation ex:location1 .


ex:location1 strdf:hasGeometry
      "x=40 and y=15"^^strdf:SemiLinearPointSet
      "t = 11"^^strdf:SemiLinearPointSet .
```

Valid time



The stRDF data model

stRDF extends sRDF with the ability to represent the **valid time** of a triple following the approach of Gutierrez et al., 2005:

Definition

- 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.

Outline

Example - Dataset I

Sensor metadata using the CSIRO/SSN ontology (Neuhaus and Compton, 2009):

```
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 .
```

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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 .
```

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") }
```

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 .
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        ?S ssn:supports ?G .
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        ?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 are optionally located 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")}}
```

Queries - Dataset I

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

```
select  ?S ?GEO
where { ?S rdf:type ssn:Sensor .
    optional {
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        ?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 (Henson et al., 2009):

```
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

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```
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 .
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ex:obs1 rdf:type om:Observation .
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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
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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:SuburbanArea .
ex:area1 ex:hasName "Dudweiller" .
ex:area1 strdf:hasGeometry
           "(-x+1.4y<=-5.3 and y<=79 and -y<=-13 and
            x-0.1y<=132) or (y<=13 and x<=133 and
           -x-1.5y<=-128)"^^strdf:SemiLinearPointSet .
```

Example - Dataset II (cont'd)

Metadata about geographical areas:

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ex:area1 rdf:type ex:SuburbanArea .
ex:area1 ex:hasName "Dudweiller" .
ex:area1 strdf:hasGeometry
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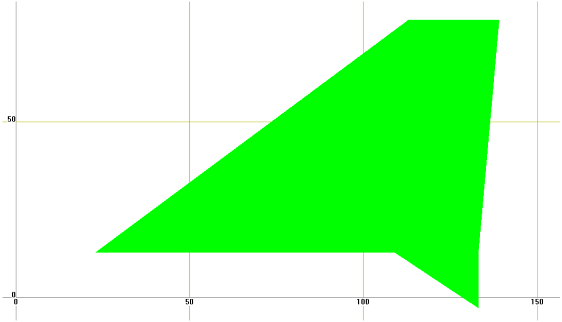
            x-0.1y<=132) or (y<=13 and x<=133 and
           -x-1.5y<=-128)"^^strdf:SemiLinearPointSet .
```



Queries - Dataset II

Spatial and temporal selection. Find the values of all observations that were valid at time 11 and the suburban 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:SuburbanArea .
        ?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) }
```

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

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select  ?V ?RA
where { ?OBS rdf:type om:Observation .
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        ?RA rdf:type ex:SuburbanArea .
        ?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" &&
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where { ?OBS rdf:type om:Observation .
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        ?R rdf:type om:ResultData .
        ?RA rdf:type ex:SuburbanArea .
        ?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

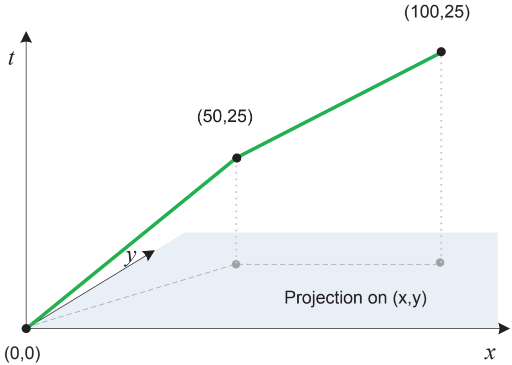
?V	?RA
"27"	ex:area1

Example - Dataset III

Moving sensor metadata using the CSIRO/SSN ontology:

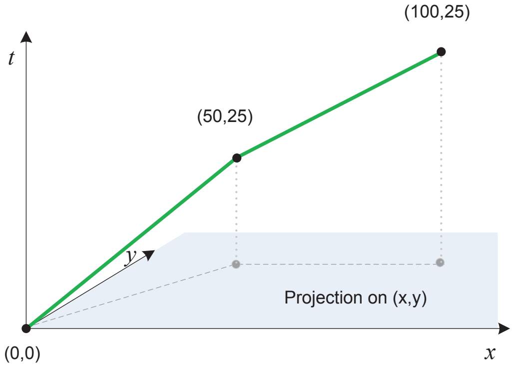
```
ex:sensor2 rdf:type ssn:Sensor .
ex:sensor2 ssn:measures ex:temperature .
ex:sensor2 ssn:supports ex:grounding2 .
ex:grounding2 rdf:type ssn:SensorGrounding .
ex:grounding2 ssn:hasLocation ex:location2 .
ex:location2 rdf:type ssn:Location .
```

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)

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```

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Metadata about geographical areas:

```
ex:area1 rdf:type ex:SuburbanArea .
ex:area1 ex:hasName "Dudweiller" .
ex:area1 strdf:hasGeometry
        "(-x+1.4y<=-5.3 and y<=79 and -y<=-13
         and x-0.1y<=132) or (y<=13 and x<=133
         and -x-1.5y<=-128)"
         ^^strdf:SemiLinearPointSet .
```

Queries - Dataset III

Intersection of an area with a trajectory. Which areas of Dudweiller 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:SuburbanArea .
        ?SN ssn:supports ?X .
        ?X ssn:hasLocation ?Y .
        ?Y strdf:hasTrajectory ?TR .
        ?RA ex:hasName "Dudweiller" .
        ?RA strdf:hasGeometry ?GEO .
        filter(?TR[1,2] overlap ?GEO) }
```

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select (?TR[1,2] INTER ?GEO) as ?SENSEDAREA ?TR[3] as ?T1
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        ?Y rdf:type ssn:Location .
        ?X rdf:type ssn:SensorGrounding .
        ?RA rdf:type ex:SuburbanArea .
        ?SN ssn:supports ?X .
        ?X ssn:hasLocation ?Y .
        ?Y strdf:hasTrajectory ?TR .
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        ?SN ssn:supports ?X .
        ?X ssn:hasLocation ?Y .
        ?Y strdf:hasTrajectory ?TR .
        ?RA ex:hasName "Dudweiller" .
        ?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+1.4y<=-5.2 and x-0.1y<=132) or (y<=13 and x<=133 and -x-1.5y<=-128))" ^^strdf:SemiLinearPointSet	"0 <= t <= 10"^^strdf: SemiLinearPointSet

What is new in stSPARQL syntax?

- *k*-ary spatial terms
  - quantifier-free formulas (**constants**)
  - **spatial variables**
  - **projections** of *k*-ary spatial terms
  - the result of **set operations** on *k*-ary spatial terms: *intersection, union, difference*
  - the result of **geometric operations** on *k*-ary spatial terms: *boundary, buffer, minimum bounding box*
- Metric spatial terms
  - *VOL, AREA, LEN, MAX, MIN*
- **Select clause**: construction of new spatial terms
  - *intersection, union, difference, projection of spatial terms*
- **Where clause**: Quad patterns to refer to the valid time of a triple
- **Filter clause**:
  - **Spatial predicates** (topological): *disjoint, touch, equals, inside, coveredby, contains, covers, overlap*
  - **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

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  - a linear equation or inequality of $\mathcal{L}$ with metric spatial terms in the place of variables

What is new in stSPARQL syntax?

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  - quantifier-free formulas (**constants**)
  - **spatial variables**
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  - the result of **set operations** on *k*-ary spatial terms: *intersection, union, difference*
  - the result of **geometric operations** on *k*-ary spatial terms: *boundary, buffer, minimum bounding box*
- Metric spatial terms
  - *VOL, AREA, LEN, MAX, MIN*
- **Select clause**: construction of new spatial terms
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- **Where clause**: Quad patterns to refer to the valid time of a triple
- **Filter clause**:
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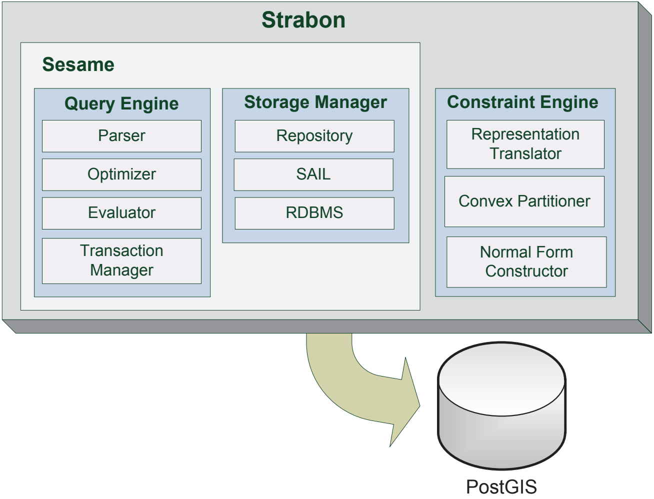
stSPARQL Semantics

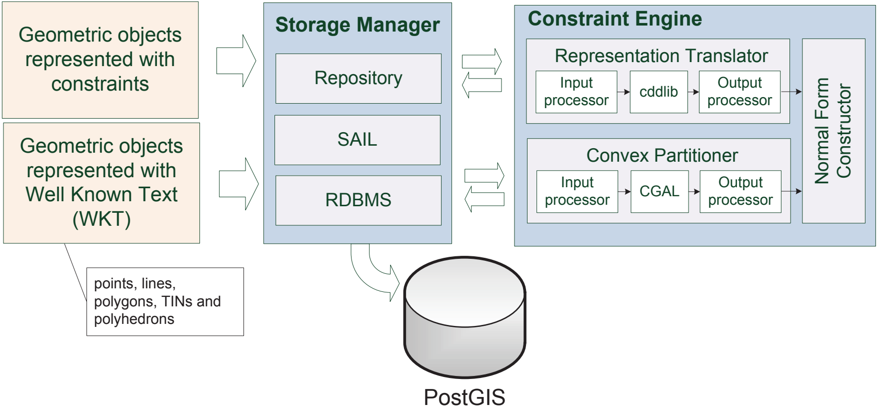
- Extension of the SPARQL semantics of (Perez et al., 2006).
  - Extend the concept of mapping
    - A variable is mapped to an element of C (quantifier-free formulas of $\mathcal{L}$ with $1,2,\ldots k$ free variables).
  - The semantics of AND, OPT, UNION remain the same.
  - We need to define carefully the evaluation of spatial terms and the semantics of spatial and temporal filters.
  - Closure property
    - The output of any operation or query is representable in stRDF.

Outline

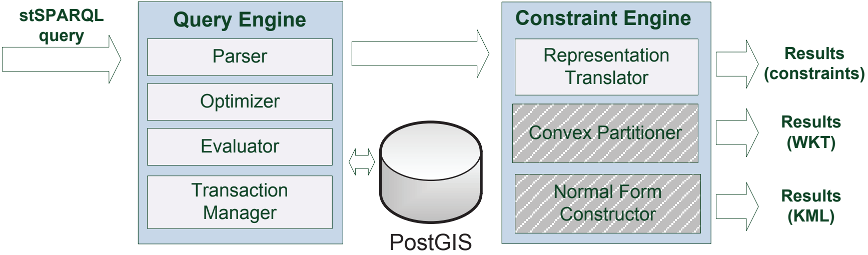
The System Strabon



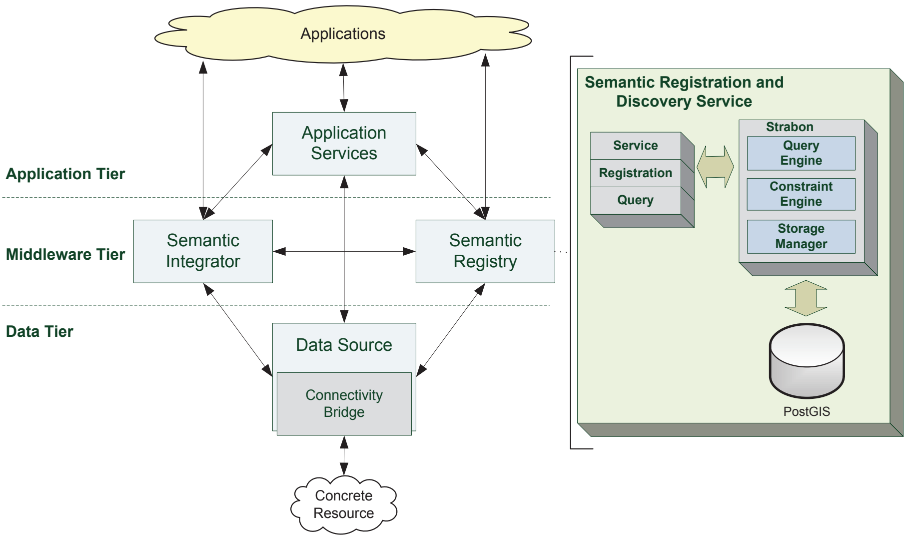
Storing stRDF Data



Evaluating stSPARQL Queries



SemsorGrid4Env Architecture and the Semantic Registry



Outline

Related Work

- Introducing Time into RDF (Gutierrez et al, 2005)
- SPARQL-ST (Perry, 2008)
- SPAUK (Kollas, 2007)
- Deep integration of spatial query processing into native RDF triple stores (Brodt et al, 2010)

Future Work

- Study the complexity of stSPARQL query processing.
- Port the implementation to MonetDB.
- Demonstrate that our approach can be implemented efficiently in comparison with competitive approaches.
- Use our implementation to publish public spatial datasets as Linked Open Data.

Thank you!

Thank you for your attention!

Fragen?