Using Grammar-based Genetic Programming for Mining Disjointness Axioms Involving Complex Class Expressions

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Motivation

- Linked Open Data (LOD) has made a huge number of interconnected RDF triples freely available for sharing and reuse
- Shared schemas and ontologies are needed to support reasoning
- Manual acquisition of axioms:
    - is exceedingly expensive and time-consuming
    - depends on the availability of domain specialists and knowledge engineers

Introduction: Ontology Learning

Top-down construction of ontologies has limitations

- aprioristic and dogmatic
- does not scale well
- does not lend itself to a collaborative effort

Bottom-up, *grass-roots* approach to ontology and KB creation

- start from RDF facts and learn OWL 2 axioms

Recent contributions towards OWL 2 ontology learning

- FOIL-like algorithms for learning concept definitions
- statistical schema induction via association rule mining
- light-weight schema enrichment (DL-Learner framework)

All these methods apply and extend ILP techniques.

Class Disjointness Axiom Learning

Problem:

We focus on learning OWL class disjointness axioms involving existential quantification ($\exists r.C$) and value restriction ($\forall r.C$)

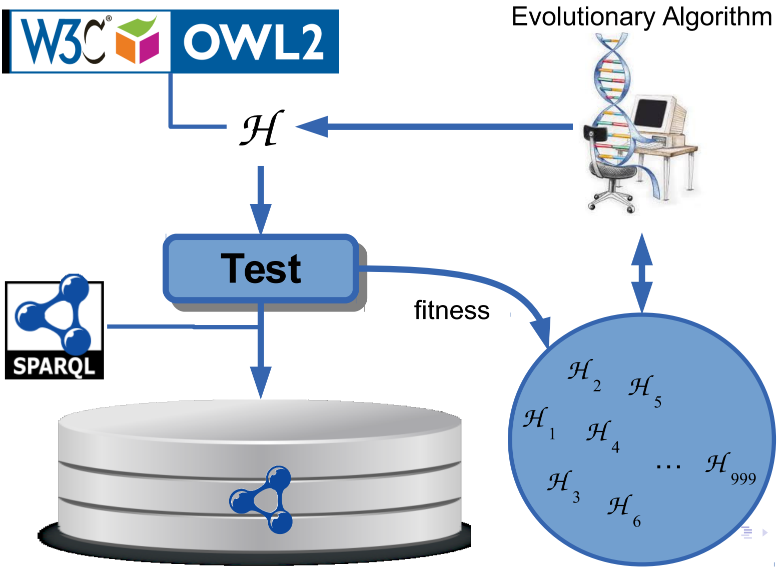
Class disjointness axioms are important

- to check the correctness of a knowledge base
- to derive new knowledge

Method:

Grammar-Based Genetic Programming

Synopsis


W3C
OWL2
Evolutionary Algorithm
$\mathcal{H}$
Test
fitness
SPARQL
$\mathcal{H}_2$ $\mathcal{H}_5$
$\mathcal{H}_1$ $\mathcal{H}_4$
... $\mathcal{H}_{999}$
$\mathcal{H}_3$ $\mathcal{H}_6$

Grammatical Evolution

- A grammar-based form of Genetic Programming
- Search space distinguished from solution (= program) space
- Search space consists of variable-length bitstrings
- Bitstrings are mapped into programs thanks to a BNF *grammar*

In the mapping process, codons are used consecutively to choose production rules in the BNF grammar according to the function:

$$\textit{production} = \textit{codon}\ \mathbf{modulo} \left[\text{Number of productions for the current non-terminal}\right]$$

Static Part of the Grammar

Axiom := ClassAxiom

ClassAxiom := DisjointClasses

DisjointClasses := 'DisjointClasses' '(' ClassExpression1 ' 'ClassExpression2 ')'

ClassExpression1 := Class
| ObjectSomeValuesFrom
| ObjectAllValuesFrom
| ObjectIntersection

ClassExpression2 := ObjectSomeValuesFrom
| ObjectAllValuesFrom

ObjectIntersectionOf := 'ObjectIntersectionOf' '(' Class ' ' Class ')'

ObjectSomeValuesFrom := 'ObjectSomeValuesFrom' '(' ObjectPropertyOf ' ' Class ')'

ObjectAllValuesFrom := 'ObjectAllValuesFrom' '(' ObjectPropertyOf ' ' Class ')'

Dynamic Part of the Grammar

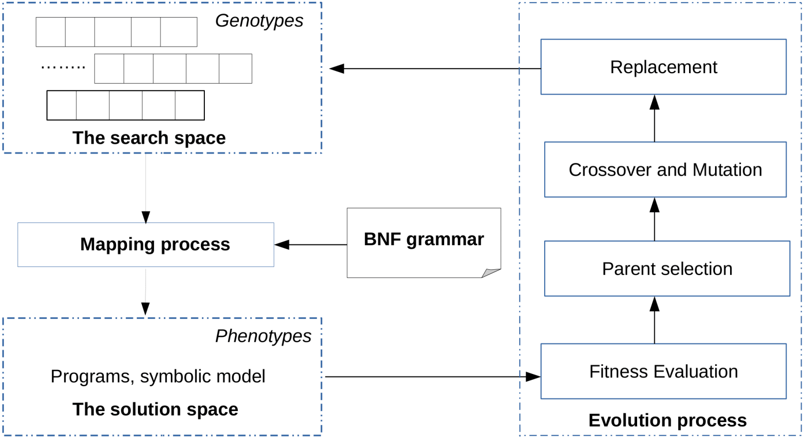
Class := ...

```
SELECT ?class
WHERE { ?instance rdf:type ?class . }
```

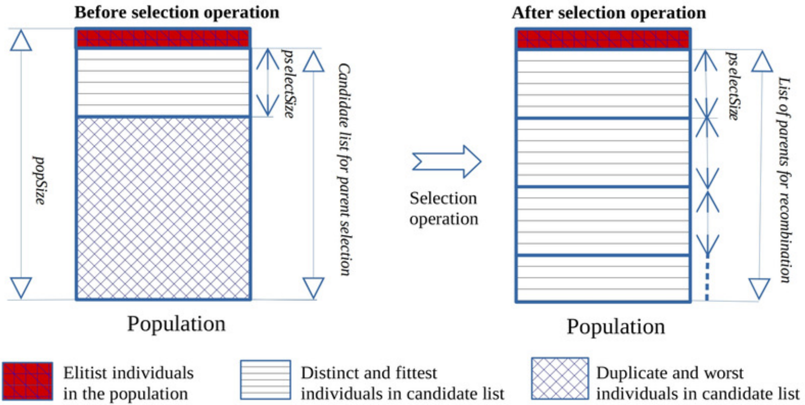
ObjectPropertyOf := ...

```
SELECT ?property
WHERE {
  ?subject ?property ?object .
  FILTER (isIRI(?object))
}
```

Grammatical Evolution Process



Parent Selection



Possibility Theory

Definition (Possibility Distribution)

$$\pi : \Omega \to [0, 1]$$

Definition (Possibility and Necessity Measures)

$$\begin{aligned} \Pi(A) &= \max_{\omega \in A} \pi(\omega); \\ N(A) &= 1 - \Pi(\bar{A}) = \min_{\omega \in \bar{A}} \{1 - \pi(\omega)\}. \end{aligned}$$

For all subsets $A \subseteq \Omega$,

1. $\Pi(\emptyset) = N(\emptyset) = 0, \quad \Pi(\Omega) = N(\Omega) = 1;$
2. $\Pi(A) = 1 - N(\bar{A})$ (duality);
3. $N(A) > 0$ implies $\Pi(A) = 1, \quad \Pi(A) < 1$ implies $N(A) = 0$.

In case of complete ignorance on A, $\Pi(A) = \Pi(\bar{A}) = 1$.

Content of an Axiom

Definition (Content of Axiom ϕ)

Given an RDF datset $\mathcal{K}$,

$$\mathrm{content}(\phi) = \{\psi : \phi \models_{\mathcal{K}} \psi\}$$

obtained through the instantiation of ψ to the vocabulary of $\mathcal{K}$.

Let $\phi = \mathsf{Dis}(C, D)$

$$\mathrm{content}(\phi) = \{\neg C(r) \vee \neg D(r) : \quad r \text{ is a resource in } \mathcal{K}\}$$

Confirmation and Counterexample of an Axiom

Given $\psi \in content(\phi)$ and an RDF dataset $\mathcal{K}$, three cases:

1. $\mathcal{K} \models \psi$: $\longrightarrow$ ψ is a *confirmation* of ϕ;
2. $\mathcal{K} \models \neg\psi$: $\longrightarrow$ ψ is a *counterexample* of ϕ;
3. $\mathcal{K} \not\models \psi$ and $\mathcal{K} \not\models \neg\psi$: $\longrightarrow$ ψ is neither of the above

Definition

Given axiom ϕ, let us define

$$u_\phi = \|content(\phi)\| \text{ (a.k.a. the } \textit{support} \text{ of } \phi)$$
$$u_\phi^+ = \text{the number of confirmations of } \phi$$
$$u_\phi^- = \text{the number of counterexamples of } \phi$$

Axiom Evaluation

Definition (Generality)

$g_\phi = \min\{\|[C]\|, \|[D]\|\}$, where C, D are class expressions.

Definition (Possibility)

$$\Pi(\phi) = 1 - \sqrt{1 - \left(\frac{u_\phi - u_\phi^-}{u_\phi}\right)^2}$$

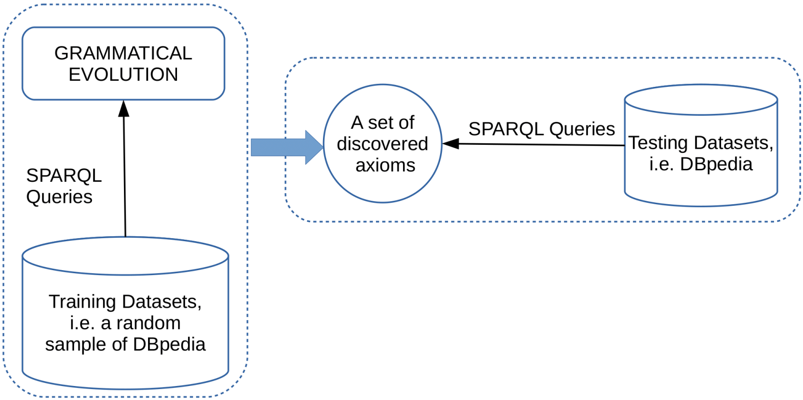
Definition (Fitness)

$$f(\phi) = g_\phi \cdot \Pi(\phi)$$

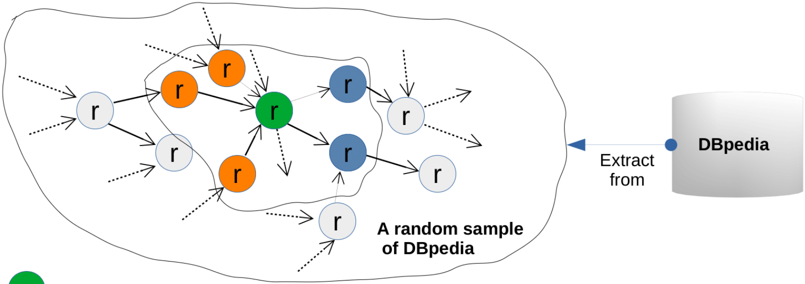
Experimental Protocol

- Training-Testing Model
- Experiments are divided into two phases:
  1. mining class disjointness axioms with GE from a training RDF dataset, i.e., a 1% random sample of DBpedia 2015-04
  2. testing the resulting axioms against the test dataset, i.e., the entire DBpedia 2015-04
- An objective benchmark to evaluate the effectiveness of the method.

Training-Testing Model



Training Set Construction



r Initial resource, e.g. *http://dbpedia.org/ontology/Plant*

r Resource as a subject in the triples relevant to r, i.e r *is the object of the extracted triple*

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Relation between resources as the predicate in the triples

Experimental Setup

- 20 different runs on different parameter settings
- To allow fair comparisons, we define total effort

$$k = \text{total number of fitness evaluations}$$

- *maxGenerations* is set so that

$$popSize \cdot maxGenerations = k$$

Parameter	**Value**
Total effort k	100,000; 200,000; 300,000; 400,000
initLenChrom	6
pCross	80%
pMut	1%
popSize	1000; 2000; 5000; 10000

Measuring Accuracy

Since $\Pi(\phi)$ may be viewed as a fuzzy degree of membership, we use a fuzzy extension of the usual definition of *precision*, based on fuzzy set cardinality

$$\|F\| = \sum_{x \in \Delta} F(x),$$

The value of precision can thus be computed against the test dataset, i.e., DBpedia 2015-04, according to the formula

$$\text{precision} = \frac{\|\text{true positives}\|}{\|\text{discovered axioms}\|} = \frac{\sum_{\phi} \Pi_{\mathrm{DBpedia}}(\phi)}{\sum_{\phi} \Pi_{\mathrm{Training}}(\phi)}$$

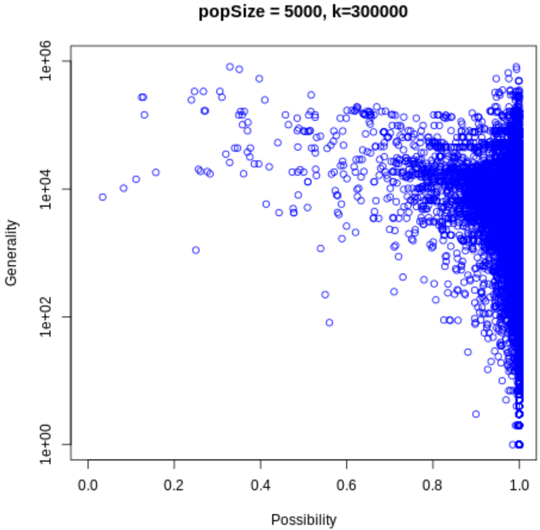
Axioms Discovered Over 20 Runs

k \ popSize	1000	2000	5000	10000
100000	8806	11389	4684	4788
200000	6204	13670	10632	9335
300000	5436	10541	53021	14590
400000	5085	9080	35102	21670

Average Precision per Run (±**std**)

k \ *popSize*	1,000	2,000	5,000	10,000
100,000	0.981 ±0.019	0.999 ±0.002	0.998 ±0.002	0.998 ±0.003
200,000	0.973 ±0.024	0.979 ±0.011	0.998 ±0.001	0.998 ±0.002
300,000	0.972 ±0.024	0.973 ±0.014	0.993 ±0.007	0.998 ±0.001
400,000	0.972 ±0.024	0.969 ±0.018	0.980 ±0.008	0.998 ±0.001

Π and g Distribution of Discovered Axioms



Examples of Discovered Axioms

Dis(∀author.Place, ∀placeofBurial.Place)	$\Pi(\phi) = 1.0;\ g_\phi = 4$
Dis(Writer, ∀writer.Agent)	$\Pi(\phi) = 0.982;\ g_\phi = 79,464$
Dis(Journalist, ∀distributor.Agent)	$\Pi(\phi) = 0.992;\ g_\phi = 32,533$
Dis(Stadium, ∀birthPlace.Place)	$\Pi(\phi) = 1.0;\ g_\phi = 10,245$

Conclusions and Future Work

- Grammar-based GP method for mining disjointness axioms involving complex class expressions
- The use of a training-testing model allows to objectively validate the method, while also alleviating the computational bottleneck of SPARQL endpoints
- The experimental results confirm that the proposed method is capable of discovering highly accurate and general axioms
- Future Work:
  - Mining disjointness axioms involving operators such as `owl:hasValue` and `owl:OneOf`
  - Forbid atomic classes at the root of class expressions
  - Refining the evaluation of candidate axioms with some measure of their complexity

The End

Thank you for your attention!