Real time reasoning in OWL2 for GDPR compliance

(AIJ 289, 2020)

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30th IJCAI, August 2021

Introduction

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- Preliminary version at IJCAI’18
  - A usage policy language $\mathcal{PL}$ based on OWL2
  - NP-completeness of $\mathcal{PL}$ and tractability of a GDPR-compatible restriction
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  - A structural subsumption algorithm for PTIME compliance checking
- New contributions
  - Tractability extended to Horn-$\mathcal{SRIQ}$ knowledge bases
  - Using Import By Query and knowledge compilation
  - Experimental scalability analysis (real time compliance checks)

$\mathcal{PL}$ Policies (BeFit Example)

Data usage policies are formalized as unions of “simple policies” i.e. $\mathcal{EL}$ concepts extended with integer intervals:

$$
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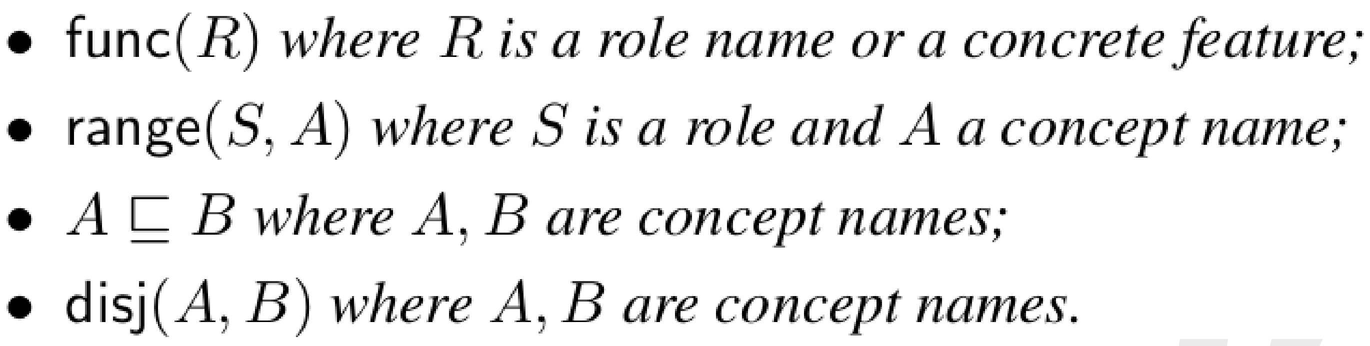
The objective part of the GDPR can be encoded in the same way

Vocabularies and Ontologies

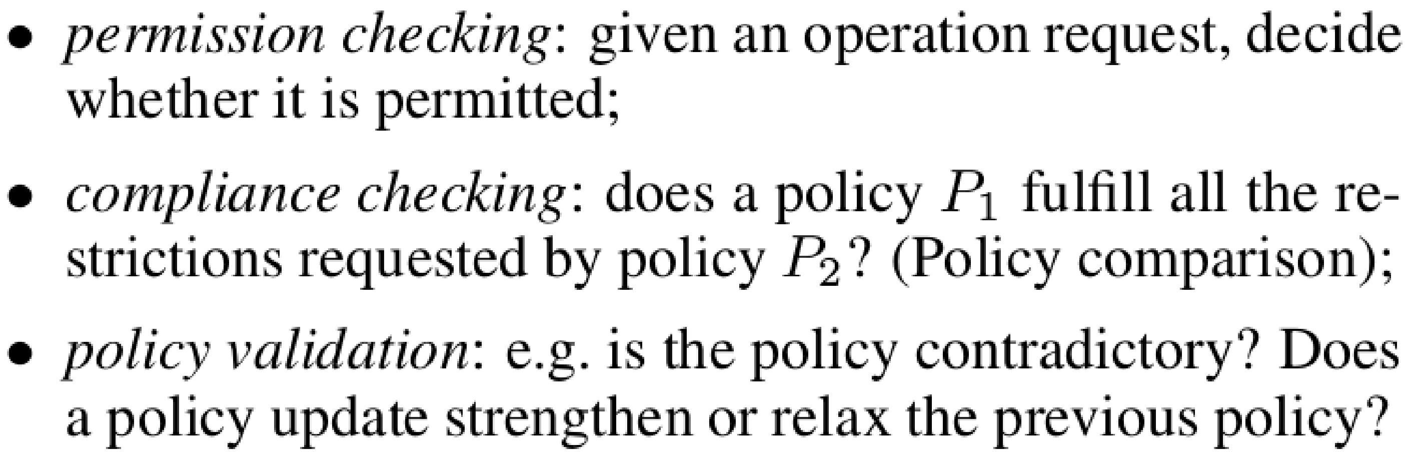
- $\mathcal{PL}$ is vocabulary-neutral. One may use for example:
  - W3C DPVCG group (Data Privacy Vocabularies) `https://www.w3.org/community/dpvcg/`
- Vocabularies are axiomatized by knowledge bases containing: (IJCAI'18 version)



- func(R) *where* R *is a role name or a concrete feature;*
- range(S, A) *where* S *is a role and* A *a concept name;*
- $A \sqsubseteq B$ *where* A, B *are concept names;*
- disj(A, B) *where* A, B *are concept names.*

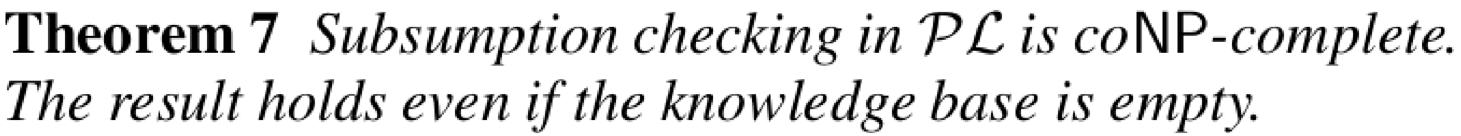
Policy reasoning tasks

- All the main reasoning tasks are reduced to concept subsumption



  - *permission checking*: given an operation request, decide whether it is permitted;
  - *compliance checking*: does a policy P_1 fulfill all the restrictions requested by policy P_2? (Policy comparison);
  - *policy validation*: e.g. is the policy contradictory? Does a policy update strengthen or relax the previous policy?

- Generally intractable due to the interplay of $[l, u](f)$ and $\sqcup$



Theorem 7 *Subsumption checking in $\mathcal{PL}$ is co*NP*-complete. The result holds even if the knowledge base is empty.*

Tractable case (IJCAI'18)

- The number of constraints $[l, u](f)$ in simple concepts is bounded by a constant
- PTIME algorithm for checking whether $KB \models P_1 \sqsubseteq P_2$:
  1. normalize the intervals $[l, u]$ of P_1 (offline) – $O(|P_1| \cdot |P_2|)$
  2. “compile” the KB into P_1 (offline) – $O(|P_1| \cdot |KB|)$
  3. apply a structural subsumption algorithm – $O(|P_1| \cdot |P_2|)$

Extension to Horn-$\mathcal{SRIQ}$ KB

- Knowledge bases are partitioned into $\mathcal{K} \cup \mathcal{O}$ where:
    - $\mathcal{K}$ is a $\mathcal{PL}$ KB that defines policy properties with “func” and “range” axioms
    - $\mathcal{O}$ is a Horn-$\mathcal{SRIQ}$ KB that defines classes and their properties (e.g. “LocationData” and its property “precision”)
    - In the policies, the roles defined in $\mathcal{O}$ may occur within the scope of those defined in $\mathcal{K}$, but not viceversa
- Reasoning is based on “Import By Query” (IBQ):
    - Normalization and structural subsumption query $\mathcal{O}$ with subsumptions of the form $A_1 \sqcap \ldots \sqcap A_n \sqsubseteq A$
    - This is the only difference from the algorithms of IJCAI’18

Main theoretical results

- Tractability and intractability extend to $\mathcal{K} \cup \mathcal{O}$, where $\mathcal{O}$ belongs to a tractable fragment of Horn-$\mathcal{SRIQ}$ (e.g. $\mathcal{EL}$ or *DL-lite*)

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- Negative results: Horn-$\mathcal{SRIQ}$ is the best we can get
  - nominals make IBQ incomplete (no Horn-$\mathcal{SROIQ}$)
  - convexity is necessary for tractability ($\mathcal{O}$ should better be *Horn*)
- Under suitable conditions (compatible with GDPR compliance), $\mathcal{O}$ can be compiled into a $\mathcal{PL}$ KB
  - then the IJCAI'18 framework applies

Another view of the theoretical framework

- $\mathcal{PL}$ policies are equivalent to *unions of conjunctive faceted queries with disequalities*
- Subsumption checking is equivalent to *containment* of such queries
- Against knowledge bases in (various fragments of) Horn-$\mathcal{SRIQ}$

Experimental evaluation

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- Test cases:
  - Random perturbation of SPECIAL's use case policies
  - Fully random policies and knowledge bases of increasing size
- Some representative results:
  - On fully random policies, and medium KB ($O(10^5)$ classes and axioms): ~ 14.7 ms (avg) per compliance check/subsumption
  - On the realistic policies: from 410 to 570 μ-sec per compliance check
  - Compares favourably with Hermit, ELK, GraphDB, and RDFox (with the standard reduction of query containment to query answering)

Summary and ongoing work

- $\mathcal{PL}$ is generally intractable, but in applications interval constraints are limited $\Rightarrow$ compliance checking is tractable
  - also when the KB is in a tractable fragment of Horn-$\mathcal{SRIQ}$
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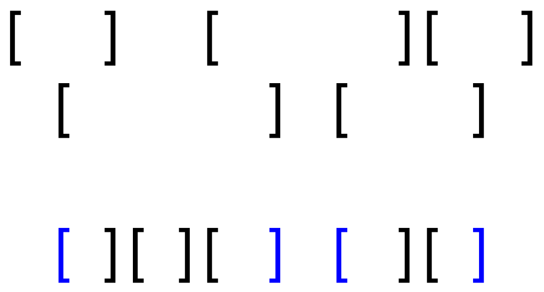
  - Questions?

Interval normalization



intervals occurring in:

P_2 : [ ] [ ][ ]

P_1 : [ ] [ ]

split P_1's

intervals : [ ][ ][ ] [ ][ ]

Afterwards, for all new $[l_1, u_1]$ and all $[l_2, u_2]$ occurring in P_2, either $[l_1, u_1] \subseteq [l_2, u_2]$ or $[l_1, u_1] \cap [l_2, u_2] = \emptyset$

Interval splitting in concepts: $[l, u](f) \rightsquigarrow [l, x_1](f) \sqcup \ldots \sqcup [x_n, u](f)$

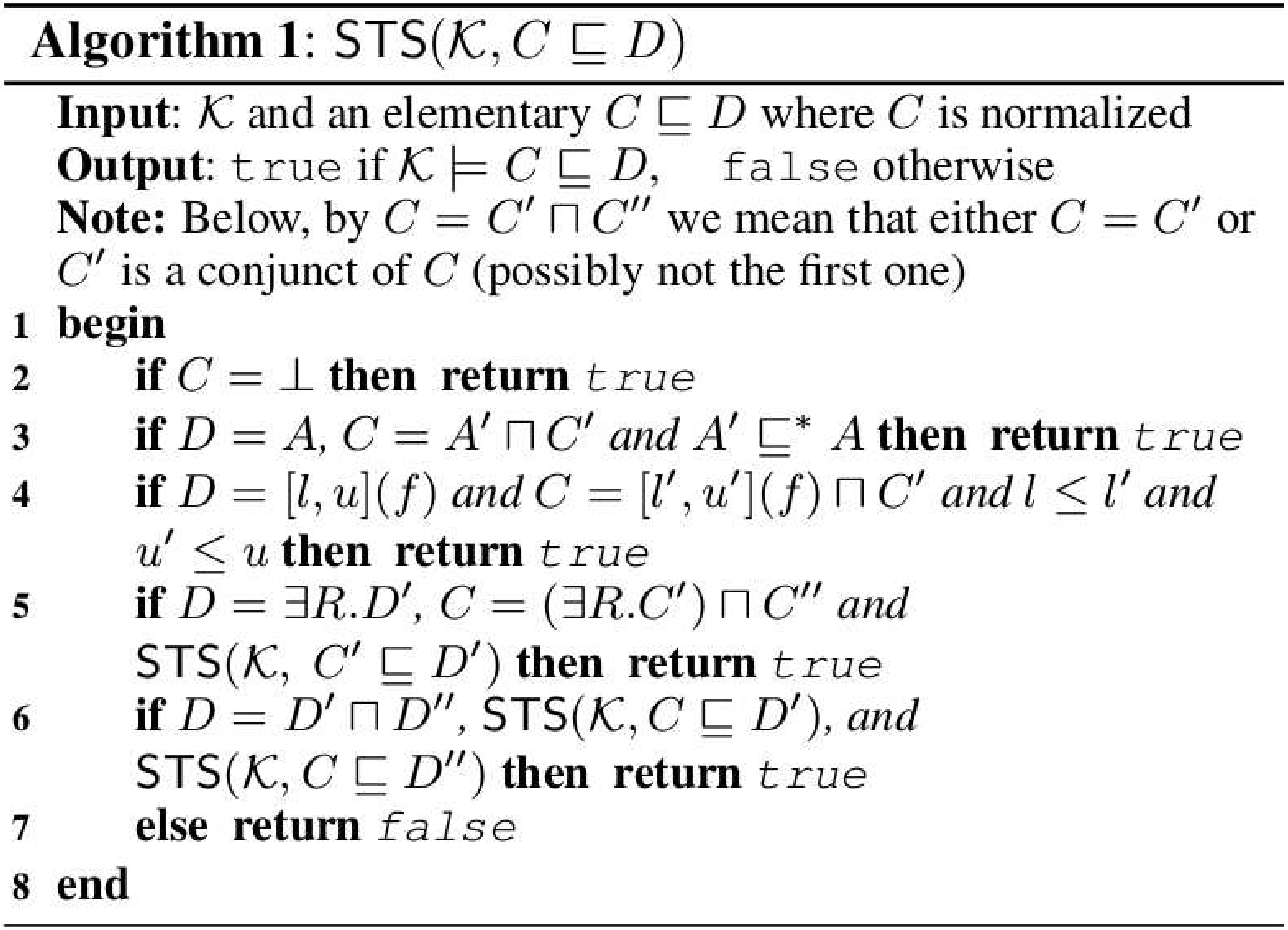
Then unions are moved to the top level using
$\exists R.(C_1 \sqcup C_2) \equiv \exists R.C_1 \sqcup \exists R.C_2$

In the tractable cases, this takes polynomial time (and space)

Second normalization phase

1) $\bot \sqcap D \leadsto \bot$
2) $\exists R.\bot \leadsto \bot$
3) $[l, u](f) \leadsto \bot$ if $l > u$
4) $(\exists R.D) \sqcap (\exists R.D') \sqcap D'' \leadsto \exists R.(D \sqcap D') \sqcap D''$ if $\mathsf{func}(R) \in \mathcal{K}$
5) $[l_1, u_1](f) \sqcap [l_2, u_2](f) \sqcap D \leadsto [\max(l_1, l_2), \min(u_1, u_2)](f) \sqcap D$ if $\mathsf{func}(f) \in \mathcal{K}$
6) $\exists R.D \sqcap D' \leadsto \exists R.(D \sqcap A) \sqcap D'$ if $\mathsf{range}(R, A) \in \mathcal{K}$ and A not a conjunct of D
7) $A_1 \sqcap A_2 \sqcap D \leadsto \bot$ if $A_1 \sqsubseteq^* A_1'$, $A_2 \sqsubseteq^* A_2'$, and $\mathsf{disj}(A_1', A_2') \in \mathcal{K}$

The structural subsumption algorithm



Algorithm 1: $\mathsf{STS}(\mathcal{K}, C \sqsubseteq D)$

```
Input: $\mathcal{K}$ and an elementary $C \sqsubseteq D$ where $C$ is normalized
Output: true if $\mathcal{K} \models C \sqsubseteq D$,    false otherwise
Note: Below, by $C = C' \sqcap C''$ we mean that either $C = C'$ or
$C'$ is a conjunct of $C$ (possibly not the first one)
begin
    if $C = \bot$ then return true
    if $D = A$, $C = A' \sqcap C'$ and $A' \sqsubseteq^* A$ then return true
    if $D = [l, u](f)$ and $C = [l', u'](f) \sqcap C'$ and $l \leq l'$ and
    $u' \leq u$ then return true
    if $D = \exists R.D'$, $C = (\exists R.C') \sqcap C''$ and
    $\mathsf{STS}(\mathcal{K},\ C' \sqsubseteq D')$ then return true
    if $D = D' \sqcap D''$, $\mathsf{STS}(\mathcal{K}, C \sqsubseteq D')$, and
    $\mathsf{STS}(\mathcal{K}, C \sqsubseteq D'')$ then return true
    else return false
end
```