Formality and Accessibility in Ontology Representation and Reasoning: A Diagrammatic Approach

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Motivation
Problem

- Ontologies: common knowledge representation paradigm
- Inaccessibility issues: unfamiliarity of domain experts with symbolic notations
- Addressing inaccessibility: visualisation facilities
- Focus of visualisation: expressing and editing ontologies vs. reasoning with and about ontologies
Proposed Solution

• Diagrammatic language: Concept Diagrams

• Diagrammatic inference rules

• Reasoner: iCon

• Empirical studies: formality and accessibility
Language
Concept Diagrams

- Diagrammatic
- Fully formalised
- Highly expressive
  - Empirical: coverage of all of OWL 2 except assertions involving ObjectHasSelf, DatatypeRestriction or constraining facets
  - Theoretical: (Conjecture) Existential Monadic Second-Order
Sara is a child.
Children only drink drinks and only those drinks that are not alcoholic.
All drinks have at least one ingredient.
• Cognitive theories support effectiveness of CDs over common node-link ontology representation approaches \(^1\)

• CDs compared to textual representation \(^2\)

• CDs compared to symbolic logics (DL and OWL) \(^3\)

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Reasoning
Inference Rules

- OWL 2 RL
  - Trades the full expressivity of OWL 2 for efficiency
  - Restriction: existential quantification to a class; union and disjoint union to class expressions
  - These restrictions allow OWL 2 RL to be implemented using rule-based technologies
Inference Rules

- **OWL 2 RL**
  - Trades the full expressivity of OWL 2 for efficiency
  - Restriction: existential quantification to a class; union and disjoint union to class expressions
  - These restrictions allow OWL 2 RL to be implemented using rule-based technologies

- 80 inference rules: (i) equality, (ii) properties, (iii) classes, (iv) class axioms, (v) datatypes, and (vi) schema vocabulary

<table>
<thead>
<tr>
<th>Name</th>
<th>If</th>
<th>then</th>
</tr>
</thead>
<tbody>
<tr>
<td>$cax - sco$</td>
<td>$T(?c_1, rdfs: subClassOf, ?c_2) \land T(?x, rdf: type, ?c_1)$</td>
<td>$T(?x, rdf: type, ?c_2)$</td>
</tr>
<tr>
<td>$cax - dw$</td>
<td>$T(?c_1, owl: disjointWith, ?c_2) \land T(?x, rdf: type, ?c_1)$</td>
<td>false</td>
</tr>
</tbody>
</table>
• Inference rules related to the semantics of classes and class axioms (24 in total)
• The mapping: atomic diagrammatic inference rules

| $cax \rightarrow dw$ | $T(?c_1, owl: disjointWith, ?c_2)$ | $T(?x, rdf: type, ?c_1)$ | $T(?x, rdf: type, ?c_2)$ | false |

- CopyCurve
- ZoneContrastHabitat
Accessibility: Reasoning and Inference Rules

- Reasoning in CDs (topo-spatial) compared to SOVA (topological) ⁴

- Comparing alternative mappings of symbolic to diagrammatic inference rules ⁵

- Guidance for Designing Multi-Premise Inference Rules

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Explanation
Explanation in Ontology Reasoning

- Justification algorithms: select minimal set of axioms responsible for an entailment

- Empirical evidence: difficult to get from justification to explanation

- Theorem proving: construct symbolic explanation for justification-entailment pairs

- Inaccessibility issues: domain experts unfamiliar with symbolic notations

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Example: Symbolic Proof

Justification axioms for an inconsistency (i.e., false entailment)

\[
\begin{align*}
\text{Cat} & \sqsubseteq \forall \text{isPetOf} . \text{Female} \quad \text{isPetOf}(\text{Rex}, \text{Alex}) \\
\text{Dis}(\text{Male}, \text{Female}) & \quad \text{Cat}(\text{Rex}) \quad \text{Male}(\text{Alex})
\end{align*}
\]

\[
\frac{\text{Cat} \sqsubseteq \forall \text{isPetOf} . \text{Female} \land \text{Cat}(\text{Rex}) \land \text{isPetOf}(\text{Rex}, \text{Alex}) \land \text{Male}(\text{Alex}) \land \text{Dis}(\text{Male}, \text{Female})}{\text{cls–avf}}
\]

\[
\frac{\text{Female}(\text{Alex}) \land \text{Male}(\text{Alex}) \land \text{Dis}(\text{Male}, \text{Female})}{\text{cax–dw}}
\]

where

\[
\frac{\text{X} \sqsubseteq \forall \text{P} . \text{Y} \land \text{X}(u) \land \text{P}(u, v)}{\text{Y}(v)} \quad \text{cls – avf}
\]

\[
\frac{\text{Dis}(\text{X}, \text{Y}) \land \text{X}(u) \land \text{Y}(u)}{\perp} \quad \text{cax – dw}
\]
Implementation: iCon
An interactive theorem prover:  

- **Input:** A theorem of form $\Delta_0 : (d_1 \wedge \cdots \wedge d_m) \Rightarrow d$
- **Inference rule application:** $\frac{\Delta}{\Delta} Rule$
- **Basic Proof State:** $\Delta_{basic} : d \Rightarrow d$
- **Output:** a formally verified diagrammatic proof

\[
\begin{align*}
\Delta_0 & \quad Rule_1 \\
\Delta_1 & \quad Rule_2 \\
\vdots & \\
\Delta_{basic} & \quad Identity
\end{align*}
\]

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Example

Initial proof state

Proof state 1

Applied inference: Copy Spider (interactive)

Proof state 2

Applied inference: Conjunction Elimination (interactive)
**Example**

**Proof state 8**

*Applied inference: Conjunction Elimination (interactive)*

**Proof state 9**

*Applied inference: Add All Missing Zones (interactive)*

**Proof state 10**

*Applied inference: Zone Contrast Habitat (interactive)*

**Proof state 11**

*Applied inference: identity (interactive)*

*Proof finished*
Evaluation
Extensibility

- Covering all OWL 2 RL inference rules
- Comparability of number of symbolic and diagrammatic rules
- Beyond OWL 2 RL
- Empirical studies
Practical Relevance and Domain Independence:

- **Case Study I: Industrial Processed-Based Modelling**

  Conceptual Error: A domain expert is trying to find all individuals that are classified as 'model process'.

  WaterTankSimpleIncomplete:process-valveTransmission is such an individual but it is not clear why because this individual is not of type 'model process'. This looks like an unintentional entailment that needs debugging.

- **Case Study II: Neurodegenerative Diseases**

  Logical Error: A domain expert would like to express that a specific individual hasPart max 0 is not related to anything under a certain property hasPart. Thus the expert adds an axiom to the ontology that defines an extra type for the individual as hasPart max 0. However, adding this axiom appears to make the ontology inconsistent, which needs debugging.
Practical Relevance and Domain Independence:

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- **Case Study II: Neurodegenerative Diseases**
  
  Logical Error: A domain expert would like to express that a specific individual data_example_1 is not related to anything under a certain property hasPart. Thus the expert adds an axiom to the ontology that defines an extra type for the individual as hasPart max 0. However adding this axiom appears to make the ontology inconsistent, which needs debugging.
Accessibility

- Language level

- Reasoning and inference rule level

- Proof level
  - Usability
    - Debugging purposes: observational advantages and heuristics
    - Communication purposes: observational advantages and step-wise explanation

- Layout: sequential vs tree layout
Conclusion and Future Work
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- Unifying diagrammatic ontology representation and reasoning
- Cognitively informed → Accessibility
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- Cognitively informed $\rightarrow$ Accessibility
- Accommodating a hybrid proof layout
- From interactive to automated theorem proving
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Thank you