Stefan Borgwardt
Technische Universität Dresden

Explaining Description Logic Reasoning

RuleML+RR'24, București, România, 18th September, 2024

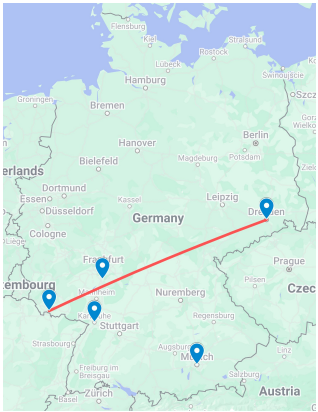
Team

Logical Reasoning

Human-Computer Interaction

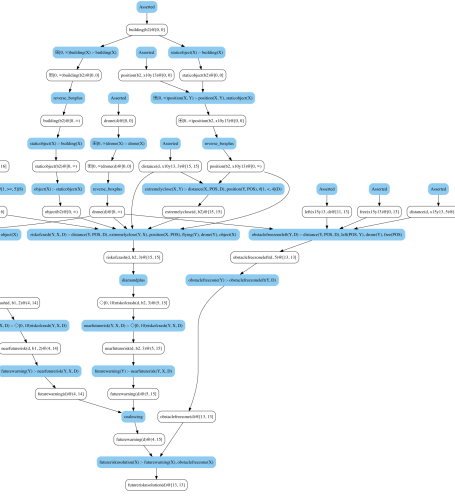
Natural Language Generation

Undergraduate students:
Tom Friese, Mikhail Kotlov, Alexej Popovič, Steffen Breuer, Anna Milena Rothermel, Duy Nhu, Kathryn Chapman, Hui-Syuan Yeh, Lukas Schmitz



Map data ©2024 GeoBasis-DE/BKG (©2009), Google, Inst. Geogr. Nacional

Explanations

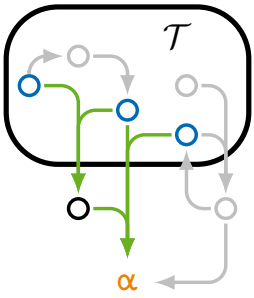


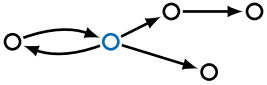
inspection time

runtime

Outline

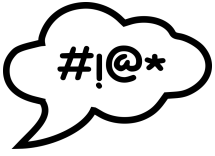
Proofs





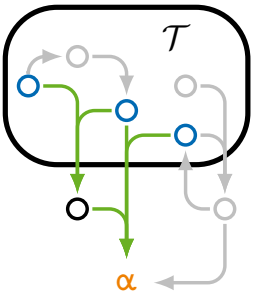
Missing entailments

User studies



Verbalization

Justifications



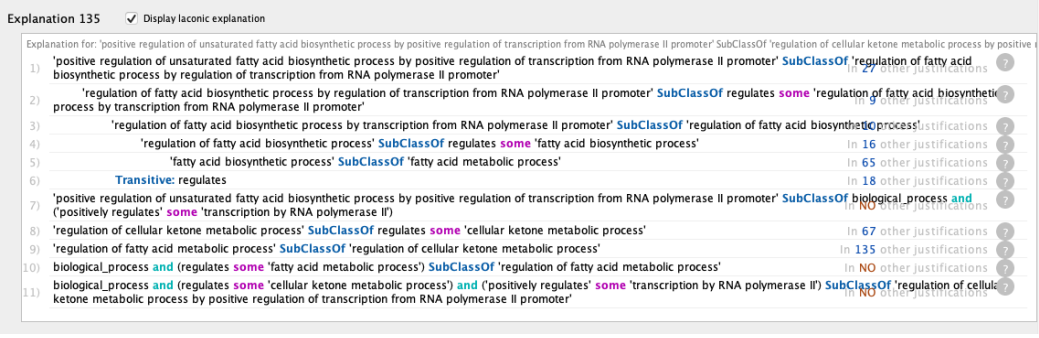
TBox (ontology, knowledge base, logical theory) $\mathcal{T}$:
Collection of axioms (formulae, rules, facts)

Entailment (consequence, query) $\mathcal{T} \models \alpha$:
Axiom (formula, rule, fact) that follows logically from the TBox

Justification (MUS, minimal conflict set, why-provenance):
Minimal subset of $\mathcal{T}$ from which α follows
(Horridge, Parsia, and Sattler 2010; Horridge, Bail, Parsia, and Sattler 2013)

Justifications are sometimes not enough for …

complex reasoning novice users LLM-generated explanations



Justification in the ontology editor Protégé

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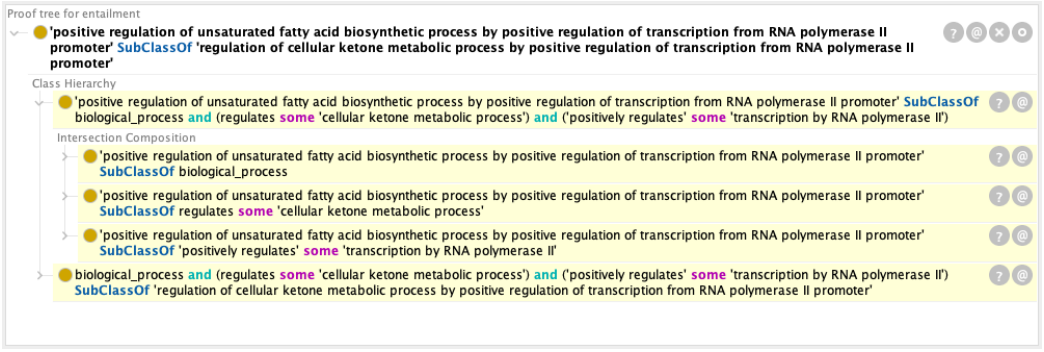
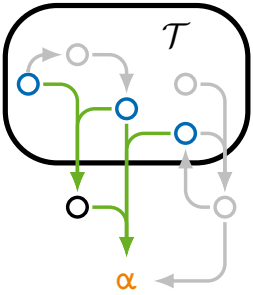


Proof in the ontology editor Protégé

Proofs are hypergraphs



Inference step (hyperedge): List of premises + conclusion

Proof: Acyclic, non-redundant hypergraph with sink α

Hypergraph $\mathfrak{D}(\mathcal{T}, \alpha)$ of all admissible inference steps for $\mathcal{T} \models \alpha$

Goal: Find optimal proofs in $\mathfrak{D}(\mathcal{T}, \alpha)$

Measures: Size (5), tree size (6), depth (2), …

Complexity of finding proofs

"Is there a proof in $\mathfrak{D}(\mathcal{T}, \alpha)$ with measure $\leq p$?"

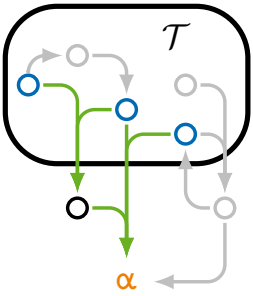
(Alrabbaa, Baader, B, Koopmann, and Kovtunova 2020, 2021)

	polynomial unary	polynomial binary	exponential unary	exponential binary
Size	NP	NP	NP	NExpTime
Monotone recursive Φ-measures	$\leq$ P	$\leq$ P	$\leq$ ExpTime	$\leq$ ExpTime
Tree size	P	P	NP	PSpace
Depth	P	P	PSpace	ExpTime
Logarithmic depth	P	P	ExpTime	ExpTime

guess proof in $\mathfrak{D}(\mathcal{T}, \alpha)$

polynomial Dijkstra-like algorithm for directed hypergraphs

Computing proofs



Consequence-based reasoners (ELK, CLIPPER, SEQUOIA)

(Kazakov, Krötzsch, and Simancik 2014; Eiter, Ortiz, Simkus, Tran, and Xiao 2012; Tena Cucala, Cuenca Grau, and Horrocks 2021)

Justification-oriented proofs

(Horridge, Parsia, and Sattler 2010)

Concept interpolation: $A \sqsubseteq ? \sqsubseteq B$

(Schlobach 2004; Peuter 2024)

Elimination proofs based on forgetting (LETHE, FAME)

(Alrabbaa, Baader, B, Koopmann, and Kovtunova 2020)

Computing proofs

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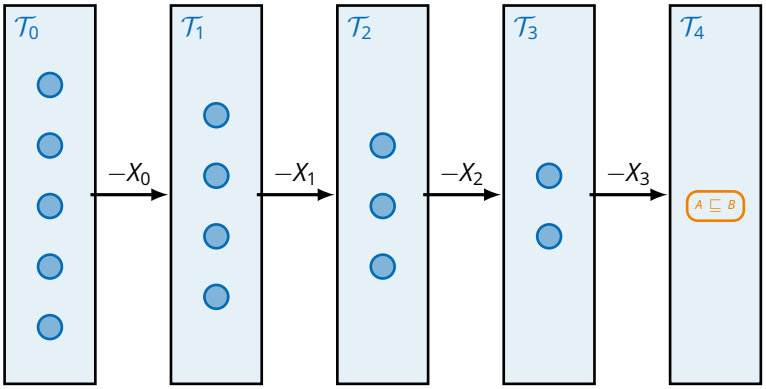

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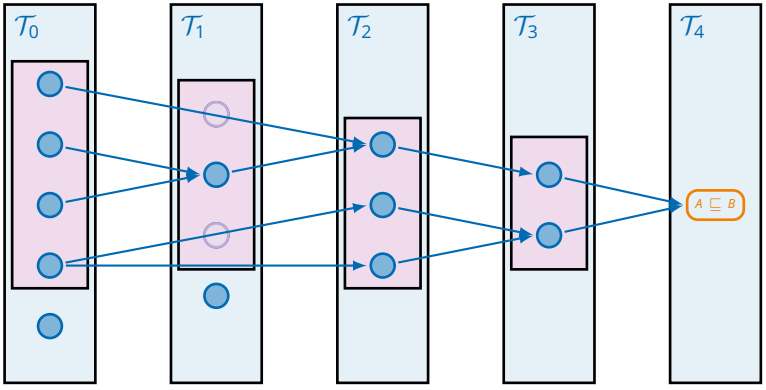

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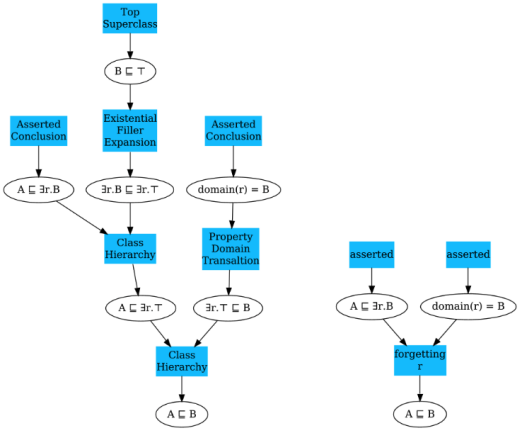
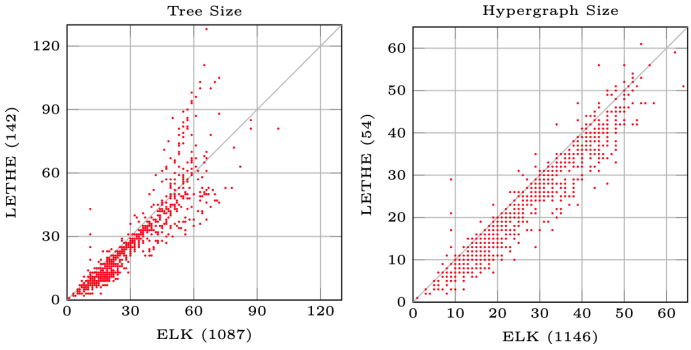


Size of proofs

(Alrabbaa, Baader, B, Koopmann, and Kovtunova 2020)

- Prototypical proofs from ORE 2015 ontologies ($\mathcal{ELH}$)
- Proof of minimal size = proof of minimal tree size



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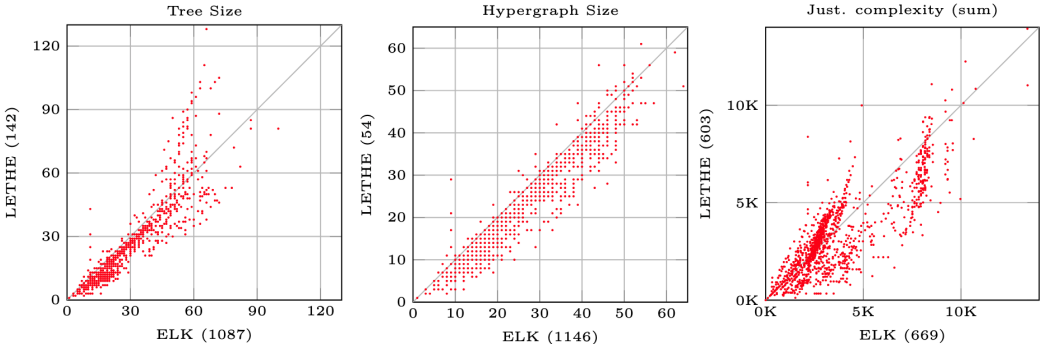
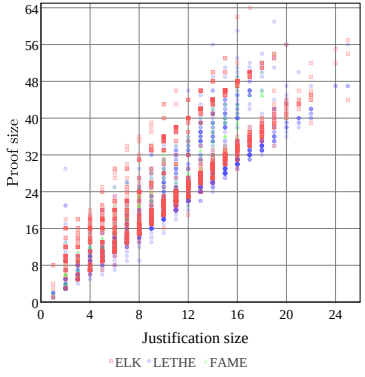
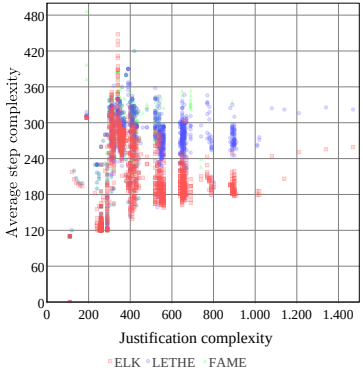


(Horridge, Bail, Parsia, and Sattler 2013)

Proofs vs. justifications

(B 2021)





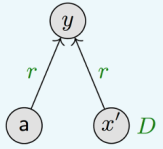
Proofs for ontology-mediated queries

(Borgida, Calvanese, and Rodriguez-Muro 2008; Alrabbaa, B, Koopmann, and Kovtunova 2022)

ABox: A(a)
TBox: $A \sqsubseteq \exists r.B$, $B \sqsubseteq \exists s.A$, $\exists s \sqcap \exists r^- \sqsubseteq E$, $\exists r.E \sqsubseteq D$

Query:

$\exists x', y.\ r(x, y) \wedge r(x', y) \wedge D(x')$



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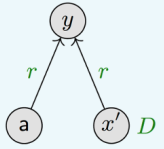

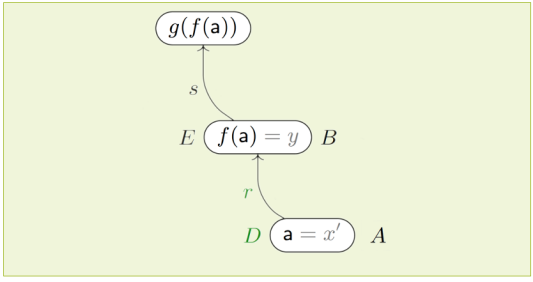

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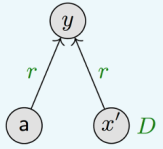

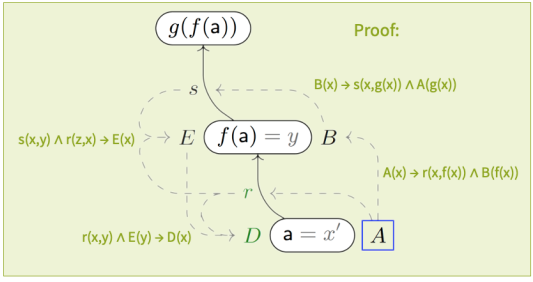

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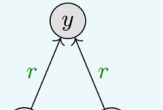

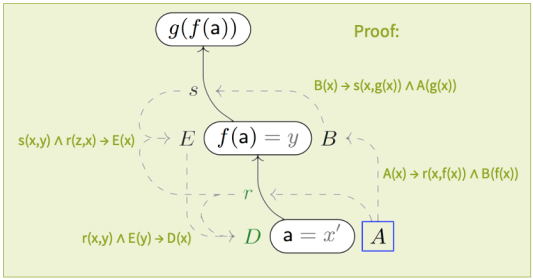

	DL-Lite		$\mathcal{EL}$		Horn-$\mathcal{ALCHOI}$
	ELQ	CQ	IQ	CQ	CQ
Domain size	NP-c		in ExpTime		in NExpTime
Tree size	in P	NP-c	P-c	NP-c	in PSpace
Proof size	NP-c		in ExpTime		
Proof size bound	polynomial		exponential		double exponential

Proofs with concrete domains

(Alrabbaa, Baader, B, Koopmann, and Kovtunova 2023)

$$[\text{fuel\_level} = 0.1 \cdot \text{fuel\_capacity}] \sqsubseteq \text{LowFuel}$$

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$$\dfrac{\dfrac{C \sqsubseteq A_\alpha \quad C \sqsubseteq A_\beta}{C \sqsubseteq A_\alpha \sqcap A_\beta} \qquad A_\alpha \sqcap A_\beta \sqsubseteq A_\gamma}{C \sqsubseteq A_\gamma}$$

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$$\dfrac{2x + 3y = 5 \qquad \dfrac{4y = 3}{-12y = -9}\,[-3]}{4x - 6y = 1}\,[2, 1]$$

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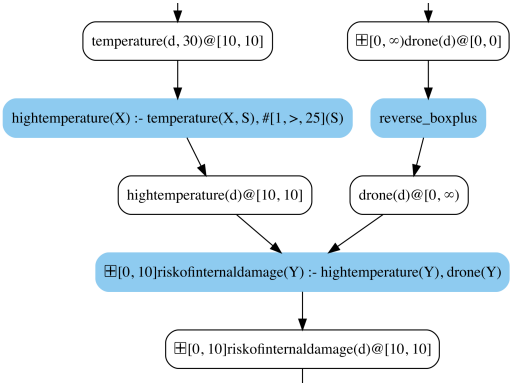
$$\Longrightarrow \quad \dfrac{C \sqsubseteq [2x + 3y = 5] \qquad \dfrac{C \sqsubseteq [4y = 3]}{C \sqsubseteq [-12y = -9]}\,[-3]}{C \sqsubseteq [4x - 6y = 1]}\,[2, 1]$$

Outlook: Proofs for rules

Proofs for DatalogMTL in MeTeoR

(B, Demberg, Jobanputra, Kovtunova, and Nhu 2024)

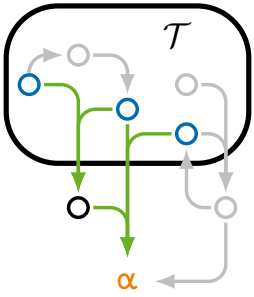


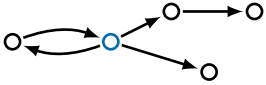
Proofs for Datalog and existential rules in Nemo

(Ivliev, Ellmauthaler, Gerlach, Marx, Meißner, Meusel, and Krötzsch 2023)

Outline

Proofs





Missing entailments

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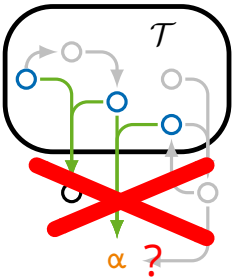
Explaining missing entailments



Missing entailment: $\mathcal{T} \not\models \alpha$

Counterexample:

Model of $\mathcal{T}$ that does not satisfy α

(Bauer, Sattler, and Parsia 2009; Alrabbaa and Hieke 2022; Alrabbaa, B, Friese, Koopmann, and Kotlov 2023)

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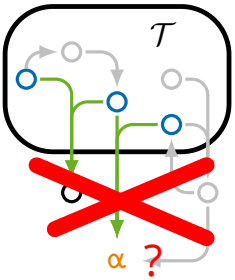

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Abductive hypothesis:

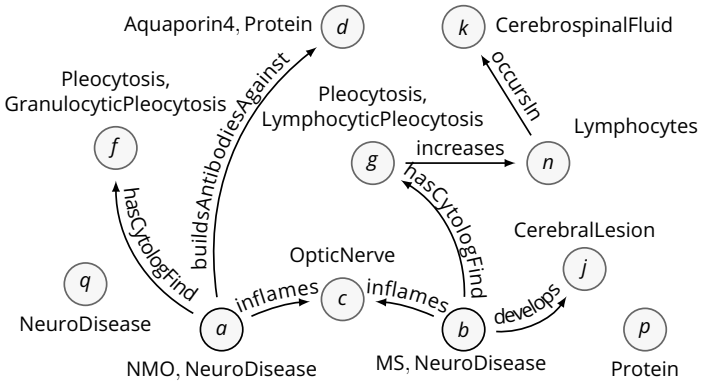
$\mathcal{H}$ such that $\mathcal{T} \cup \mathcal{H} \models \alpha$ $\quad (\mathcal{T} \cup \mathcal{H} \not\models \bot$ and $\mathcal{H} \not\equiv \{\alpha\})$

(Calvanese, Ortiz, Simkus, and Stefanoni 2013; Wei-Kleiner, Dragisic, and Lambrix 2014; Koopmann, Del-Pinto, Tourret, and Schmidt 2020; Haifani, Koopmann, Tourret, and Weidenbach 2022)

Relevant counterexamples

Model of $\mathcal{T}$ that does not satisfy NeuromyelitisOptica $\sqsubseteq$ MultipleSclerosis

(Alrabbaa and Hieke 2022)



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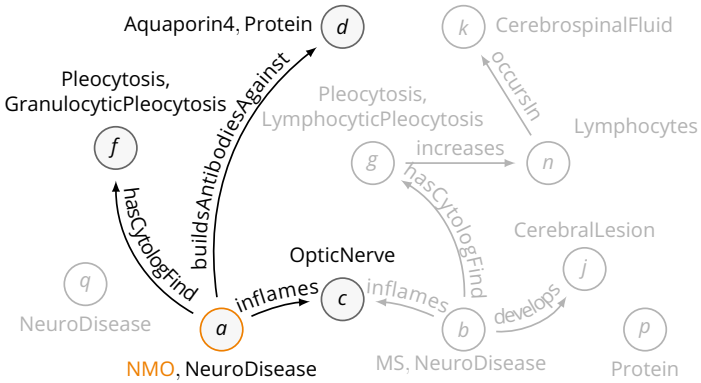

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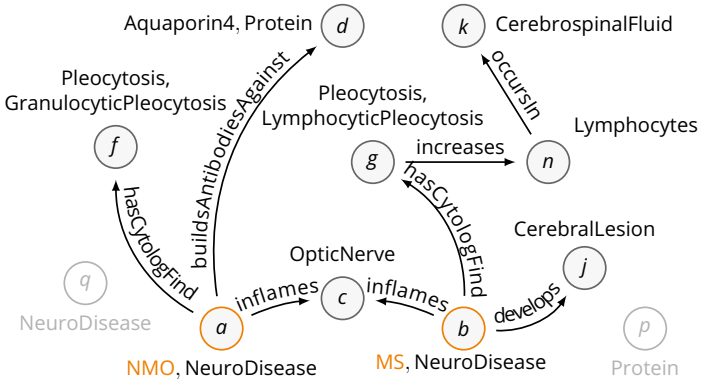

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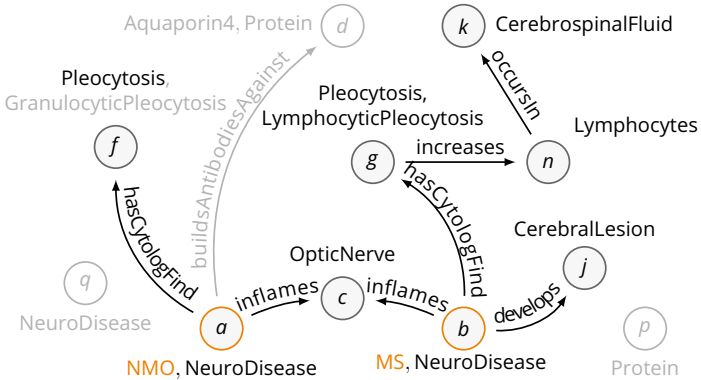

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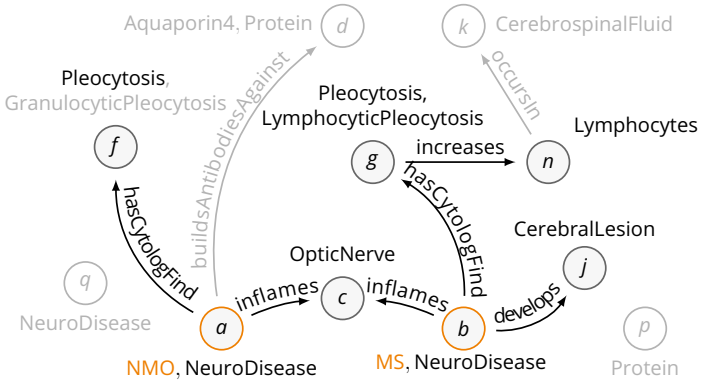

Abduction

$\mathcal{H}$ such that $\mathcal{T} \cup \mathcal{H} \models \alpha$ ($\mathcal{T} \cup \mathcal{H} \not\models \bot$ and $\mathcal{H} \not\equiv \{\alpha\}$)

Complete signature-based abduction

(Koopmann, Del-Pinto, Tourret, and Schmidt 2020)

- Restrict $\mathcal{H}$ to a signature Σ
- High expressivity: $\mathcal{T}$ in $\mathcal{ALC}$, $\mathcal{H}$ with disjunction of axioms, inverse roles, nominals, fixpoint concepts
- Implementation based on LETHE

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Connection-minimal abduction

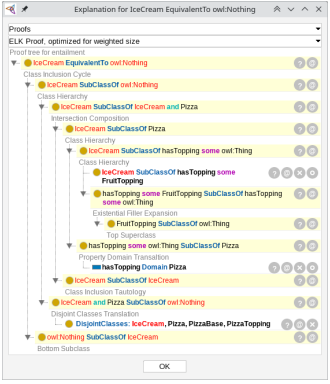
(Haifani, Koopmann, Tourret, and Weidenbach 2022)

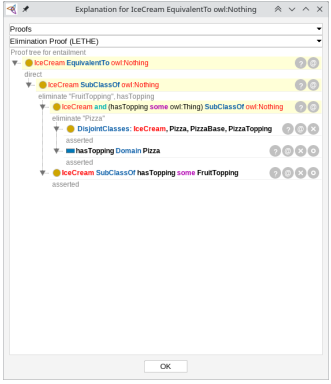
- $\mathcal{H}$ is "connected" to α
- Low expressivity: $\mathcal{T}$ in $\mathcal{EL}$, $\mathcal{H}$ only conjunctions of concept names
- Implementation (Capi) based on Spass

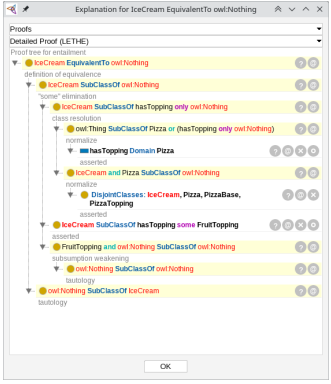
(Non)commercial break

EVEE – a collection of PROTÉGÉ plugins

github.com/
de-tu-dresden-inf-lat/evee







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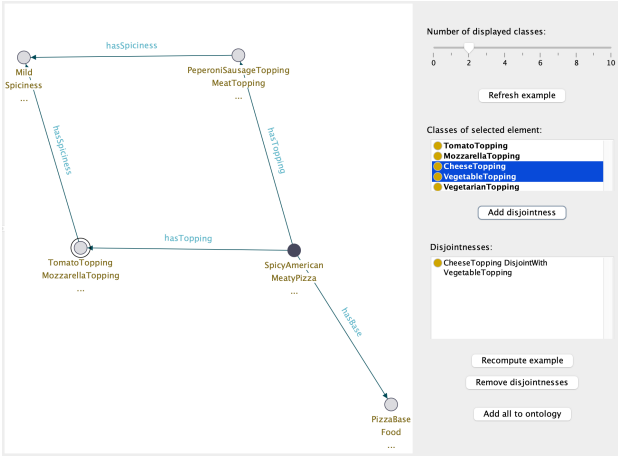
EVEE – a collection of PROTÉGÉ plugins



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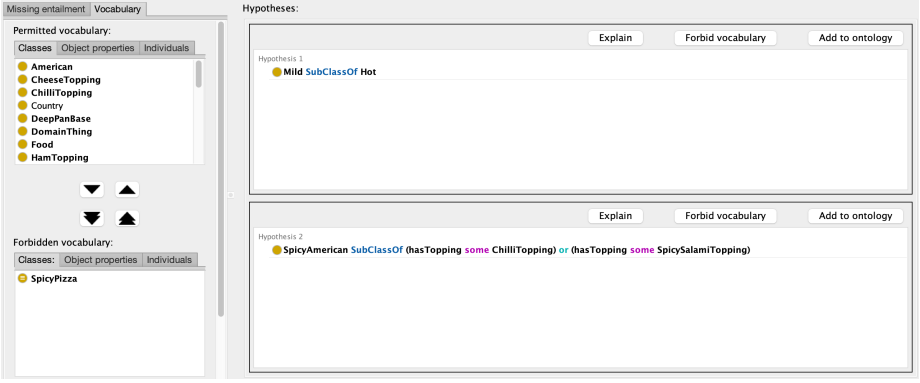

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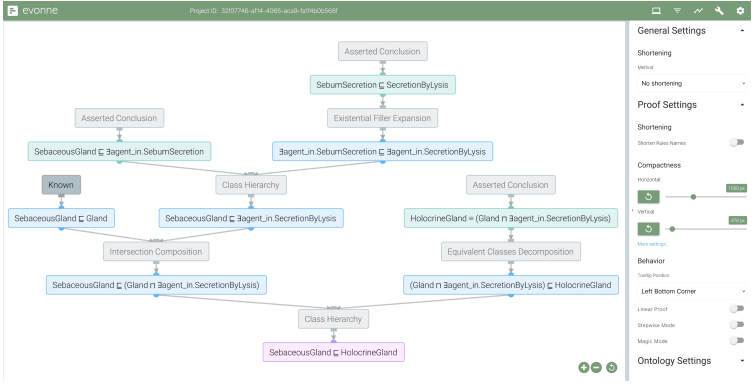
EVONNE – EVEE's bigger sister

imld.de/evonne



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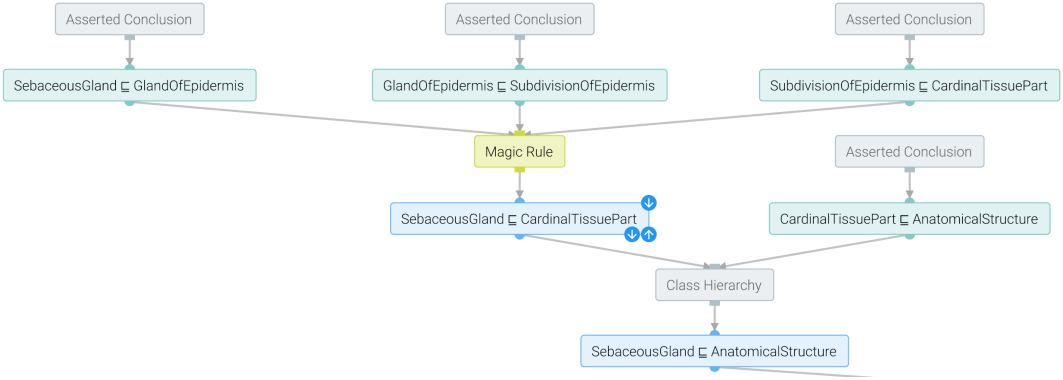

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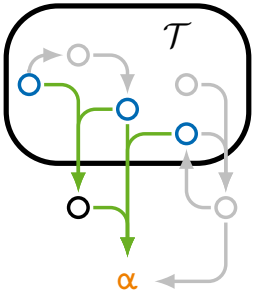
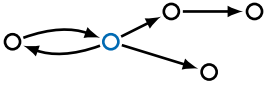
Outline

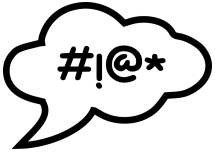
Proofs





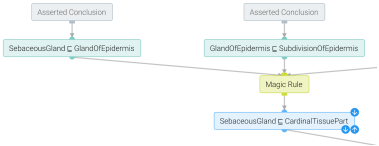
Missing entailments

User studies



Verbalization

User studies

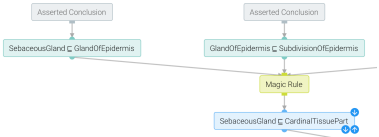


Proof format

(Alrabbaa, B, Hirsch, Knieriemen, Kovtunova, Rothermel, and Wiehr 2022)

- Many prefer shorter, tree-shaped, interactive proofs
- Preferences are subjective
- IQ test (ICAR16) predicts performance on proofs

User studies



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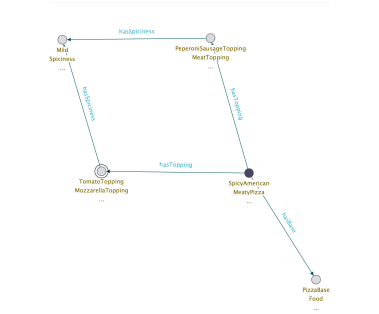

Usability of EVEE

(Alrabbaa, B, Friese, Hirsch, Knieriemen, Koopmann, Kovtunova, Krüger, Popovič, and Siahaan 2024)

- Preferred explanation methods depend on users and use cases

Designing user studies

domain-specific / abstract performance / preferences experts / students / laypeople

Since every cell culture is a material object and every material object contains an atom, every cell culture contains an atom. From the facts that every cell culture contains an atom and that every cell culture contains a cell and contains only cells, it follows that every cell culture contains something which is both an atom and a cell.

Every cell is a compound. Thus, any object which is an atom and a cell at the same time is also an atom and a compound. There is no object which is an atom and a compound at the same time. Therefore, there is no object which is both an atom and a cell.

Furthermore, since every cell culture contains something which is both an atom and a cell and there is no object which is both an atom and a cell, there is no cell culture.

Designing user studies

domain-specific / abstract performance / preferences experts / students / laypeople

$$\dfrac{\dfrac{\mathsf{CClt} \sqsubseteq \exists \mathsf{ct}.\mathsf{C} \sqcap \forall \mathsf{ct}.\mathsf{C} \qquad \dfrac{\mathsf{CClt} \sqsubseteq \mathsf{MaObj} \qquad \mathsf{MaObj} \sqsubseteq \exists \mathsf{ct}.\mathsf{At}}{\mathsf{CClt} \sqsubseteq \exists \mathsf{ct}.\mathsf{At}}}{\mathsf{CClt} \sqsubseteq \exists \mathsf{ct}.(\mathsf{At} \sqcap \mathsf{C})} \qquad \dfrac{\dfrac{\mathsf{C} \sqsubseteq \mathsf{Cmp}}{\mathsf{At} \sqcap \mathsf{C} \sqsubseteq \mathsf{At} \sqcap \mathsf{Cmp}} \qquad \mathsf{At} \sqcap \mathsf{Cmp} \sqsubseteq \bot}{\mathsf{At} \sqcap \mathsf{C} \sqsubseteq \bot}}{\mathsf{CClt} \sqsubseteq \bot}$$

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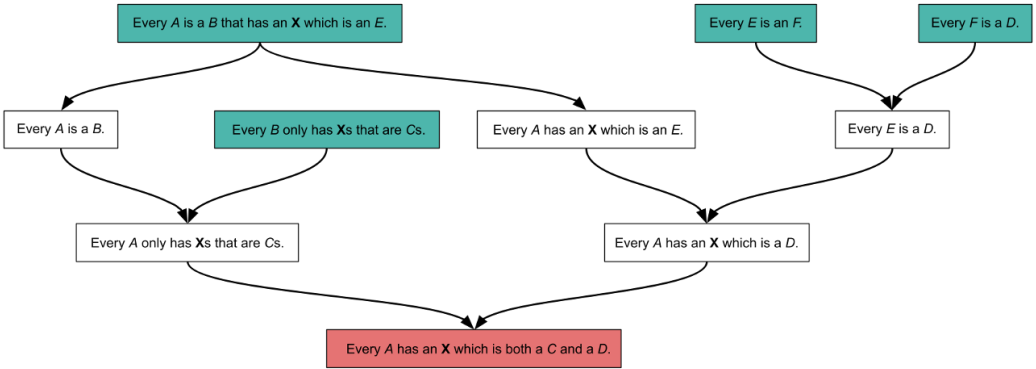


Designing user studies

domain-specific / abstract performance / preferences experts / students / laypeople

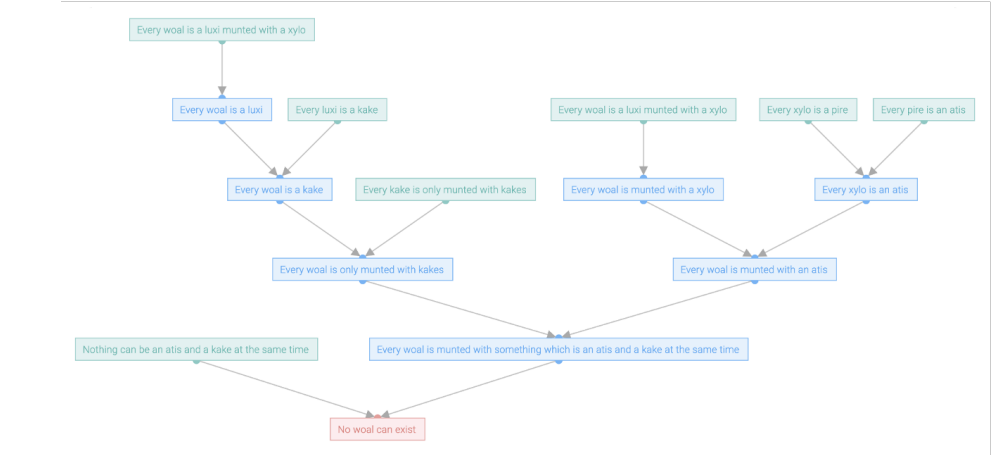
Since every woal is a luxi that is munted with a xylo,
every woal is a luxi.
Since every luxi is a kake,
every woal is a kake.
Moreover, every kake is only munted with kakes,
and thus every woal is only munted with kakes.

Every xylo is a pire
and every pire is an atis,
which means that every xylo is an atis.
Since every woal is a luxi that is munted with a xylo,
every woal is munted with a xylo.
Since every xylo is an atis,
we know that every woal is munted with an atis.

We have inferred that every woal is only munted with kakes
and that every woal is munted with an atis.
Therefore, every woal is munted with something which is both an atis and a kake.
However, nothing can be an atis and a kake at the same time
which lets us conclude that woals cannot exist.

Designing user studies

domain-specific / abstract performance / preferences experts / students / laypeople



Outline

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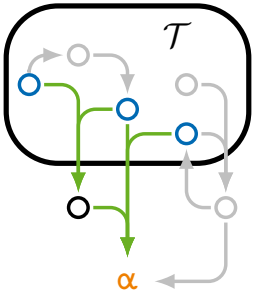

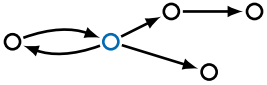

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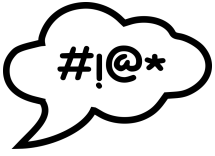

Verbalization

Drone handover scenario

Handover from autonomous drone to human operator
requires timely, short warning of a critical situation

(Wiehr, Hirsch, Schmitz, Knieriemen, Krüger, Kovtunova, B, Chang, Demberg, Steinmetz, and Hoffmann 2021)

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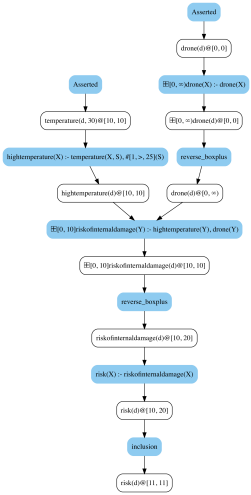
Verbalization of entailments and explanations:

- controlled natural language (Power 2012)
- template-based verbalization (Schiller, Schiller, and Glimm 2017)
- transformer models (Chang, Kovtunova, B, Demberg, Chapman, and Yeh 2022)
- large language models (B, Demberg, Jobanputra, Kovtunova, and Nhu 2024)

Proof verbalization with LLMs



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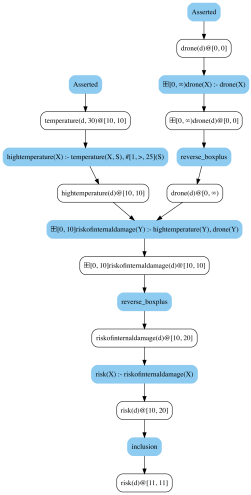
Proofs provide more information than justifications

Proof verbalization with LLMs



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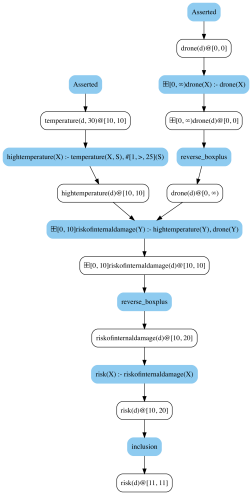
Challenge: Find the important parts of the proof

Proof verbalization with LLMs



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Proofs provide more information than justifications

Challenge: Find the important parts of the proof

> "At time 10, there is a risk of internal damage to your drone (d) because it has a high temperature of 30 degrees Celsius. This is likely because the drone is flying."

Inconsistent outputs, hallucinations

Summary

- Justifications are often enough, but sometimes proofs are needed
- Missing entailments also require explanations
- Computing explanations can take a long time
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Thank you!

References I

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References IV

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