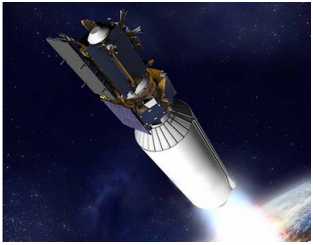
Dresden University of Technology

Stefan Borgwardt
Technische Universität Dresden

Automated Planning with Ontologies

DL Seminar, March 27, 2026

Planning and reasoning



AI planning

- dynamic
- actions modify abstract states
- low-level action knowledge
- fixed domain
- closed-world assumption

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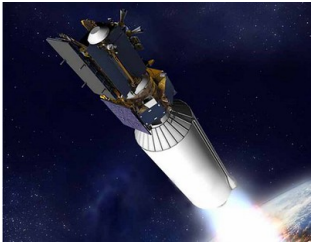


AI planning

- dynamic
- actions modify abstract states
- low-level action knowledge
- fixed domain
- closed-world assumption

Knowledge representation and reasoning

- static
- global state constraints
- high-level background knowledge
- open domain
- open-world assumption

Outline

Preliminaries

- Planning domain definition language (PDDL)
- Description logics (DLs)
- Explicit-input knowledge and action bases (eKABs)

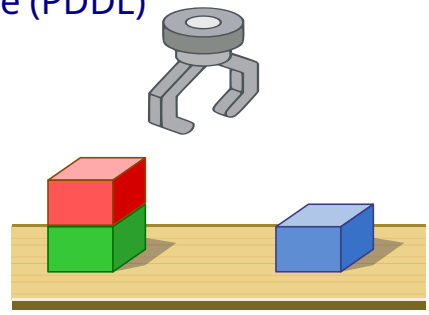
(Calvanese, Montali, Patrizi, and Stawowy 2016)

Optimizing the DL-Lite compilation (B, Hoffmann, Kovtunova, and Steinmetz 2021)

Compilations for Horn DLs (B, Hoffmann, Kovtunova, Krötzsch, Nebel, and Steinmetz 2022)

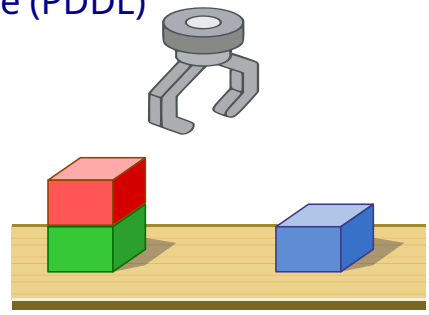
Coherent updates for DL-Lite (B, Nhu, and Röger 2025)

Planning domain definition language (PDDL)



Planning domain definition language (PDDL)

Predicates: `on/2`, `clear/1`, `table/1`



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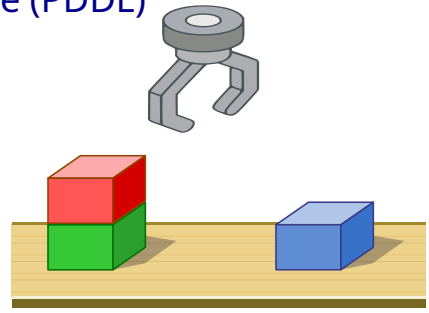

Predicates: `on`/2, `clear`/1, `table`/1

Action: `move`

Parameters: $\langle x, y \rangle$

Precondition: $\texttt{clear}(x) \wedge \texttt{clear}(y) \wedge \neg\texttt{table}(x)$

Effects:

$\texttt{on}(x, y)$

If $\neg\texttt{table}(y)$, then $\neg\texttt{clear}(y)$

For all z, if $\texttt{on}(x, z)$, then $\texttt{clear}(z)$ and $\neg\texttt{on}(x, z)$

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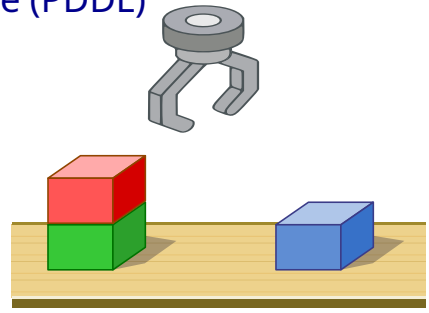

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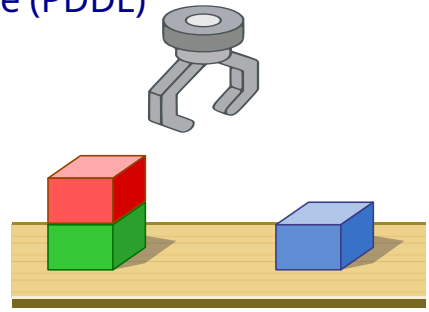

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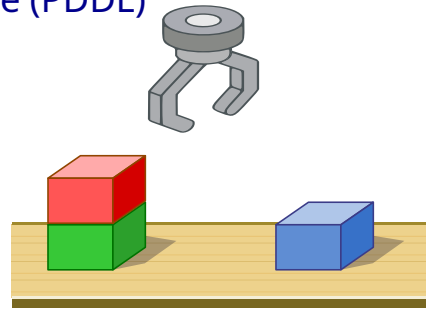

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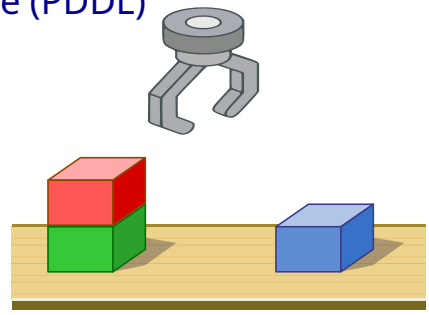

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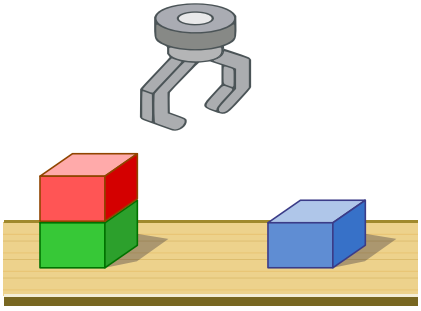
PDDL task $(\mathcal{P}, \mathcal{A}, \mathcal{O}, I, G)$

PDDL action effects

Action $(\vec{x}, pre, eff)$:

- parameters $\vec{x}$
- precondition formula *pre*
- conditional effects $(\vec{y}, cond, add, del)$:



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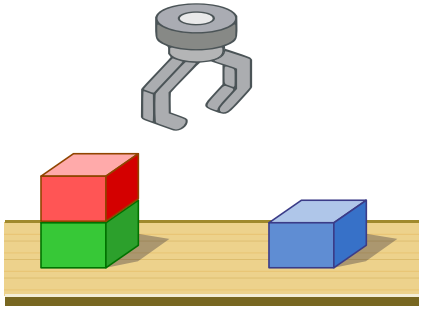

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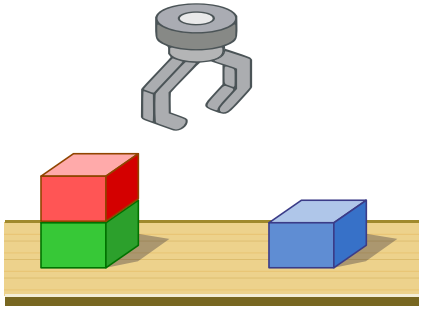

State *s*: set of ground atoms (*facts*)

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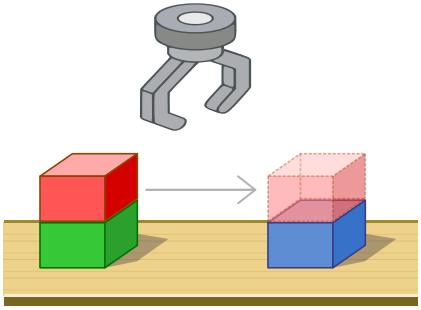

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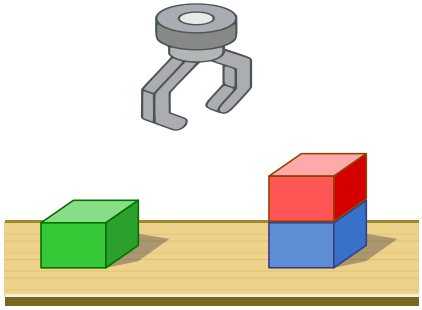

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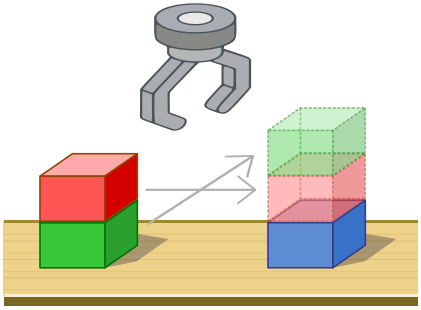

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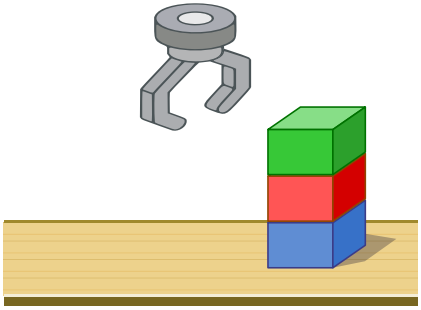

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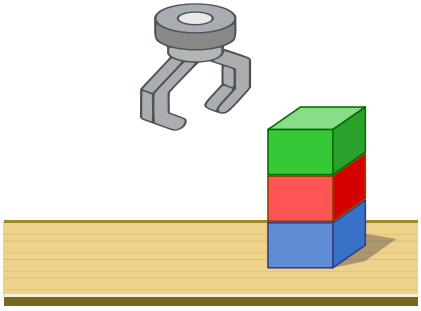
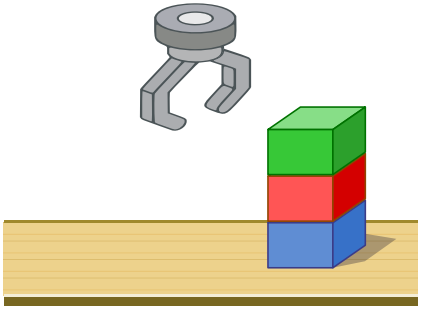
PDDL properties

- many planning benchmarks, competitions
- first-order formulas in conditions and goal
- closed-world, closed-domain states



PDDL properties

- many planning benchmarks, competitions
- first-order formulas in conditions and goal
- closed-world, closed-domain states
- checking conditions is PSPACE-complete
- plan existence is EXPSPACE-complete
- all facts updated explicitly, lots of bookkeeping



(Erol, Nau, and Subrahmanian 1995)

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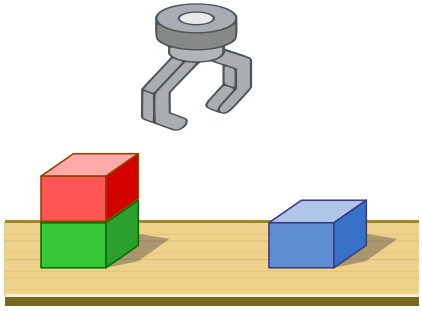
Decidable fragments of FOL with a funny syntax
(and only unary and binary predicates)



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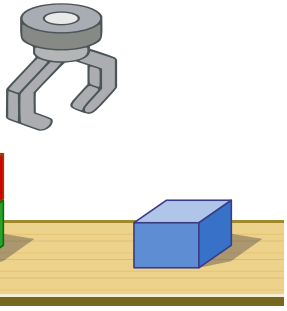

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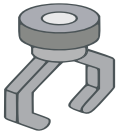

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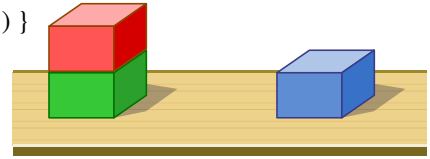

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$\texttt{Clear} \equiv \neg\texttt{Blocked},\ \texttt{Block} \sqsubseteq \exists \texttt{onblock} \sqcup \exists \texttt{ontable},\ \texttt{Robot} \sqsubseteq\ = 2\,\texttt{hand}\ \}$

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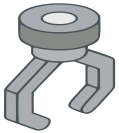

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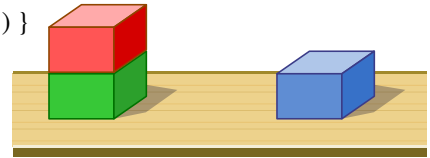

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Some (Horn) DLs: DL-Lite, $\mathcal{ELH}_\bot$, Horn-$\mathcal{ALCHOIQ}$, Horn-$\mathcal{SROIQ}$, ~~$\mathcal{ALCI}$, $\mathcal{SH}$~~, ...

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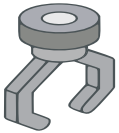

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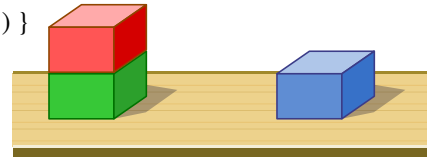

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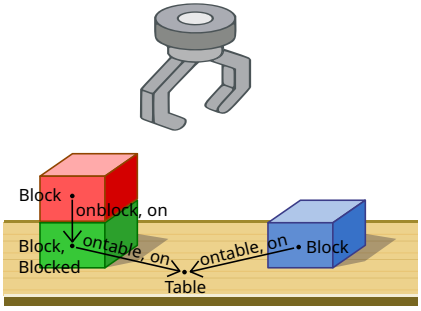
Conjunctive queries (CQs): $q(x, z) = \exists y.\ \texttt{on}(x, y) \wedge \texttt{on}(y, z)$

DL semantics

Defined on first-order interpretations $\mathcal{I}$



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- Models: $\mathcal{I} \models \mathcal{T}, \mathcal{I} \models s$
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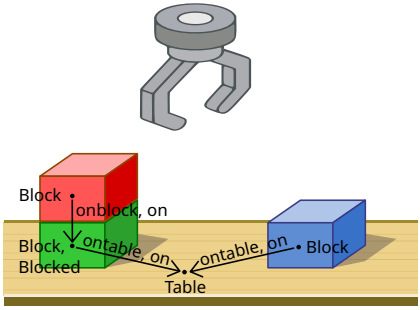

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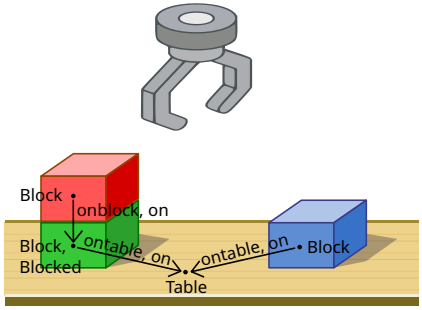

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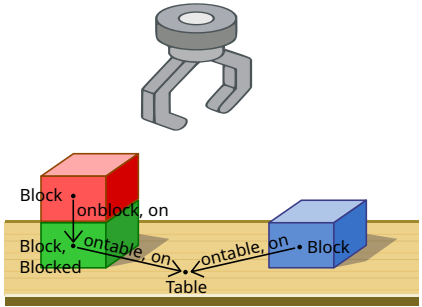

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- Open-world, open-domain reasoning
- Complexity of CQ entailment ranges from NP to 2ExpTime

Rewriting CQs over DL Ontologies

FO-rewriting: Encode $q(\vec{x})$ and $\mathcal{T}$ into FO-formula $q_{\mathcal{T}}(\vec{x})$

Property: For all ABoxes s, $\underbrace{s, \mathcal{T} \models q(\vec{c})}_{\text{open-world}} \iff \underbrace{\mathcal{I}_s \models q_{\mathcal{T}}(\vec{c})}_{\text{closed-world}}$

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- Simpler to evaluate (PSPACE, NP)
- Introduced for DL-Lite
- May be very large

(Calvanese, De Giacomo, Lembo, Lenzerini, and Rosati 2007;
Artale, Calvanese, Kontchakov, and Zakharyaschev 2009)

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Datalog-rewriting: For all ABoxes s, $s, \mathcal{T} \models q(\vec{a}) \iff s, \mathcal{R}_{\mathcal{T},q} \models q(\vec{a})$

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- no existential rules like $\exists y.\texttt{on}(x, y) \leftarrow \texttt{Block}(x)$ ($\texttt{Block} \sqsubseteq \exists \texttt{on}$ in DLs)
- closed-domain, unique minimal model, ExpTime-complete
- rewritings exist for $\mathcal{ELH}_\bot$ (polynomial size), Horn-$\mathcal{SHIQ}$ (exponential size), ...

(Eiter, Ortiz, Šimkus, Tran, and Xiao 2012; Bienvenu and Ortiz 2015)

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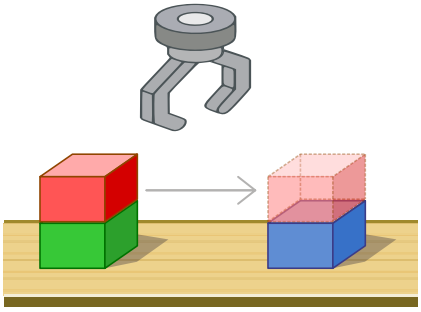

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Action $\texttt{move}(x, y)$:

Precondition:

$\neg[\texttt{Blocked}(x)] \wedge \neg[\texttt{Blocked}(y)] \wedge [\texttt{Block}(x)]$

Effects:

If $[\texttt{Table}(y)]$, then $\texttt{ontable}(x, y)$

If $[\texttt{Block}(y)]$, then $\texttt{onblock}(x, y)$

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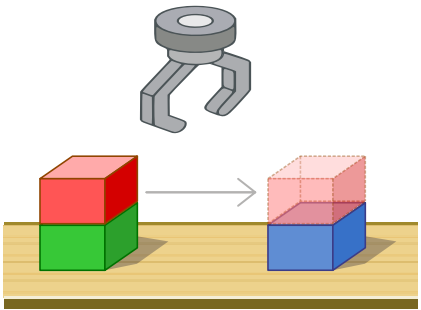

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- separate static part (ontology) and dynamic part (actions)
- epistemic evaluation of ECQ conditions depends on the ontology language (PSPACE^C)

Compiling eKABs into PDDL

DL-Lite: use FO-rewriting to replace CQs by FO formulas

$[\texttt{Block}(x)] \rightsquigarrow$
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Theorem (cf. Calvanese, Montali, Patrizi, and Stawowy 2016)

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- $[q(\vec{x})]$ can result in large DNF
- DNF for $\neg[q(\vec{x})]$ exponentially larger

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PDDL 2.2 to the rescue!

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- more expressive than stratified Datalog$^\neg$ (Röger and Grundke 2024)
- plan existence remains ExpSpace-complete

Compilation with derived predicates

$\neg[\texttt{Blocked}(x)]$

compile $\rightsquigarrow$ $\neg\big(\texttt{Blocked}(x) \vee \exists y.\texttt{onblock}(y,x)\big)$

replace $\rightsquigarrow$ $\neg\texttt{Aux}(x)$ with rule $\texttt{Aux}(x) \leftarrow \texttt{Blocked}(x) \vee \exists y.\texttt{onblock}(y,x)$

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KR'21 experiments

- compare to original compilation (Calvanese, Montali, Patrizi, and Stawowy 2016)
- planning: FD 20.06 (Helmert 2006)

KR'21 experiments

- compare to original compilation (Calvanese, Montali, Patrizi, and Stawowy 2016)
- planning: FD 20.06 (Helmert 2006)
- benchmarks:
  - 125 DL-Lite eKAB tasks from different sources (Hoffmann, Weber, Scicluna, Kacmarek, and Ankolekar 2008; Calvanese, Montali, Patrizi, and Stawowy 2016)
  - 80 classical planning tasks with complex conditions

KR'21 results

Domain	#	# solved Orig	# solved KR21	preprocessing time (s) Orig	preprocessing time (s) KR21
Cats	20	14	20	68.34	0.14
Elevator	20	20	20	0.35	0.29
Robot	20	4	20	15.03	10.09
TaskAssign	20	3	20	0.81	0.12
TPSA	15	14	5	1.42	1.83
VTA	15	15	13	1.32	304.23
VTA-Roles	15	15	5	2.25	11.61
Assembly	30	30	30	0.22	0.55
GridPlacement	20	6	20	49.80	7.01
Miconic	30	9	9	56.61	0.33
Overall	**205**	**130**	**162**	**28.23**	**18.61**

Overall better, though not in all domains

Also useful for classical planning tasks

Outline

Preliminaries

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- Description logics (DLs)
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Optimizing the DL-Lite compilation (B, Hoffmann, Kovtunova, and Steinmetz 2021)

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Compiling Horn DL eKABs into PDDL

"(stratified) Datalog$^{\neg}$ rewriting $\subseteq$ PDDL derived predicates"

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$\neg[\texttt{Block}(x)] \overset{\text{compile}}{\rightsquigarrow} \neg q(x)$ with rules

$$
\begin{aligned}
q(x) &\leftarrow \texttt{Block}(x) \\
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Theorem (B, Hoffmann, Kovtunova, Krötzsch, Nebel, and Steinmetz 2022)

There is a compilation scheme from Datalog$^{\neg}$ rewritable eKABs into PDDL with derived predicates that preserves plan length.

Compilation size

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There is a compilation scheme from Datalog$^\neg$ rewritable eKABs into PDDL with derived predicates that preserves plan length.

Corollary

There is a polynomial-size compilation scheme from $\mathcal{ELH}_\bot$ eKABs into PDDL with derived predicates that preserves plan length.

(Bienvenu and Ortiz 2015)

Corollary

There is an exponential-size compilation scheme from Horn-$\mathcal{SHIQ}$ eKABs into PDDL with derived predicates that preserves plan length.

(Eiter, Ortiz, Šimkus, Tran, and Xiao 2012)

AAAI'22 experiments

- compilation scheme using Datalog rewriting for Horn-$\mathcal{SHIQ}$ (Clipper)
  (Eiter, Ortiz, Šimkus, Tran, and Xiao 2012)
- compare to (Calvanese, Montali, Patrizi, and Stawowy 2016; B, Hoffmann, Kovtunova, and Steinmetz 2021)

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- compare to (Calvanese, Montali, Patrizi, and Stawowy 2016; B, Hoffmann, Kovtunova, and Steinmetz 2021)
- benchmarks:
  - 125 previous DL-Lite eKAB tasks
  - 110 new, more expressive tasks

AAAI'22 results

Domain	#	# solved			planning time (s)		
		Cal16	KR21	AAAI22	Cal16	KR21	AAAI22
Cats	20	14	20	20	63.46	0.13	0.03
Elevator	20	20	20	20	0.36	0.30	0.03
Robot	20	4	12	20	15.05	10.10	0.11
TaskAssign	20	3	20	20	0.81	0.12	0.06
TPSA	15	14	5	15	2.01	2.42	0.30
VTA	15	15	13	15	23.06	371.56	16.91
VTA-Roles	15	15	5	15	2.25	11.61	1.36
Overall	**125**	**85**	**95**	**125**	**19.99**	**77.33**	**3.59**
Drones	24			20			101.42
Queens	30			15			21.66
RobotConj	56			56			8.14
Overall	**110**			**91**			**30.87**

Solves all DL-Lite tasks very quickly

Compilation itself also much faster on average

Feasible also for more expressive ontologies

Horn-$\mathcal{ALCHOIQ}$

What about more expressive DLs?

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Combined rewriting for Horn-$\mathcal{ALCHOIQ}$: (Carral, Dragoste, and Krötzsch 2018)

- exponential Datalog program using types $R(x, t_D) \wedge D(t_D) \leftarrow C(x)$
- complex filtration phase "check whether $F_{q,\sigma}$ is a rooted directed forest"

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- represent types using Datalog^S set terms (Ortiz, Rudolph, and Šimkus 2010)
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Unless ExpTime^{NP} = ExpTime, there can be no polynomial-size compilation scheme from Horn-$\mathcal{SROIQ}$ eKABs to PDDL with derived predicates that preserves plan length polynomially.

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- CQ entailment for Horn-$\mathcal{SROIQ}$ is 2ExpTime-hard (Ortiz, Rudolph, and Šimkus 2010)
- Horn-$\mathcal{SROIQ}$ eKABs (non-uniformly) simulate universal 2ExpTime Turing machine

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- Horn-$\mathcal{SROIQ}$ eKABs (non-uniformly) simulate universal 2ExpTime Turing machine
- polynomial-size compilation into PDDL with polynomial plan length (ExpTime)
  ⇒ 2ExpTime ⊆ ExpTime/poly
  ⇒ weak exponential hierarchy collapses (Buhrman and Homer 1992)

Non-Horn DLs?

Similar arguments work for $\mathcal{SH}$, $\mathcal{ALCI}$ eKABs (CQ entailment also 2ExpTime-hard)
(Lutz 2008; Eiter, Lutz, Ortiz, and Šimkus 2009)

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Unless ExpTime^{NP} = ExpTime, there is no polynomial-size compilation scheme from Horn-$\mathcal{SROIQ}$ / $\mathcal{SH}$ / $\mathcal{ALCI}$ eKABs to PDDL with derived predicates that preserves plan length polynomially.

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Shortcomings of eKABs (I)

Action effects ignore the ontology

$\mathcal{T} = \{$ funct onblock, $\exists$onblock $\sqsubseteq \neg\exists$ontable, … $\}$

Action move(x, y):

Precondition:

$\neg$[Blocked(x)] $\wedge$ $\neg$[Blocked(y)] $\wedge$ [Block(x)]

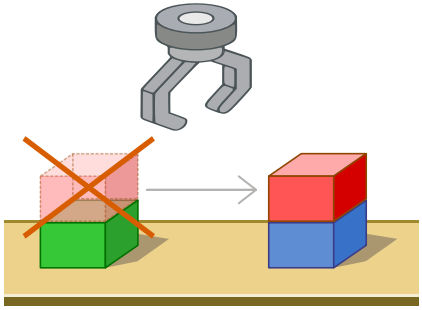
Effects:

If [Table(y)], then ontable(x, y)

If [Block(y)], then onblock(x, y)

For all z, if ontable(x, z), then $\neg$ontable(x, z)

For all z, if onblock(x, z), then $\neg$onblock(x, z)



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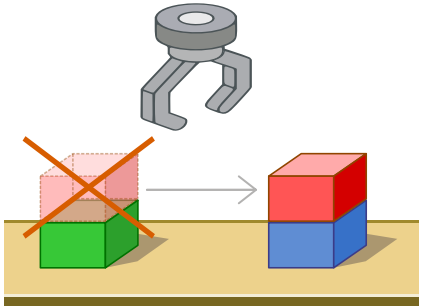


Problem I

Old, conflicting `ontable`/`onblock` facts are not removed automatically

Shortcomings of eKABs (II)

Action effects ignore the ontology

$\mathcal{T} = \{\ \texttt{onblock} \sqsubseteq \texttt{on},\ \texttt{ontable} \sqsubseteq \texttt{on},\ \ldots\ \}$

Action $\texttt{move}(x, y)$:

Precondition:

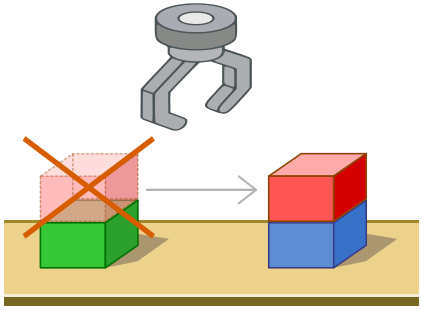
$\neg[\texttt{Blocked}(x)] \wedge \neg[\texttt{Blocked}(y)] \wedge [\texttt{Block}(x)]$

Effects:

If $[\texttt{Table}(y)]$, then $\texttt{ontable}(x, y)$

If $[\texttt{Block}(y)]$, then $\texttt{onblock}(x, y)$

For all z, if $[\texttt{on}(x, z)]$, then $\neg\texttt{on}(x, z)$



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Action `move`(x, y):

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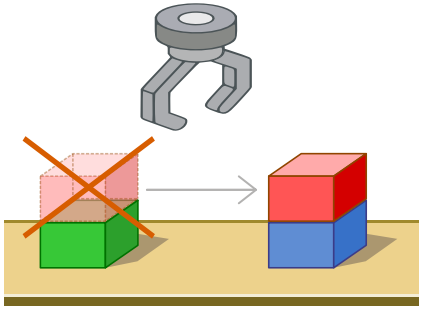

Problem II

`ontable`/`onblock` facts are not removed automatically when deleting `on` facts

Shortcomings of eKABs (III)

Action effects ignore the ontology

$\mathcal{T} = \{\ \texttt{Block} \equiv \exists \texttt{on},\ \exists \texttt{onblock}^{-} \sqsubseteq \texttt{Block},\ \ldots\ \}$

Action $\texttt{move}(x, y)$:

Precondition:

$\neg[\texttt{Blocked}(x)] \wedge \neg[\texttt{Blocked}(y)] \wedge [\texttt{Block}(x)]$

Effects:

If $[\texttt{Table}(y)]$, then $\texttt{ontable}(x, y)$

If $[\texttt{Block}(y)]$, then $\texttt{onblock}(x, y)$

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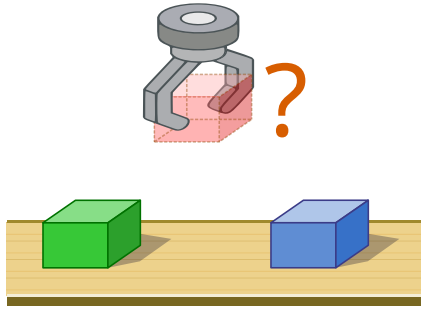

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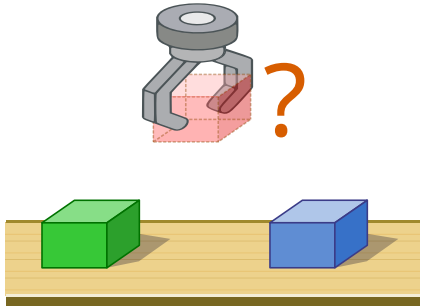

Problem III

Implicit `Block` facts can be lost if `ontable`/`onblock` facts are removed

Coherence update semantics

Given: ABox s, ground sets *Add*, *Del* (union of all applicable effects)

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Goal: ABox s' such that

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- $s', \mathcal{T} \not\models f$ for all $\neg f \in \mathit{Del}$
- $s', \mathcal{T}$ are consistent
- $s', \mathcal{T}$ preserves a maximal subset of facts entailed by $s, \mathcal{T}$ (minimal change)

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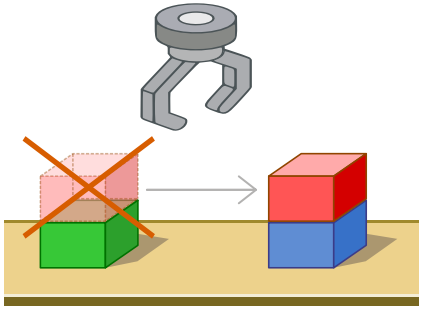
Coherence update s' for DL-Lite ontologies (Giacomo, Oriol, Rosati, and Savo 2021)

- Unique updated ABox s', unless *Add* and *Del* are contradictory
- Can be computed by stratified Datalog$^\neg$ rules $\mathcal{R}_{\mathit{Add},\mathit{Del}}$, for any ABox s

Coherent movement of blocks

$Del = \{\texttt{on}(\texttt{r}, \texttt{g})\}$

$\rightsquigarrow$ remove $\texttt{onblock}(\texttt{r}, \texttt{g})$ (II), add $\texttt{Block}(\texttt{r})$ (III)



Coherent movement of blocks

Del = {on(r, g)}
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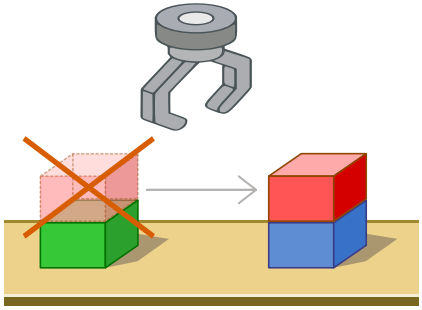

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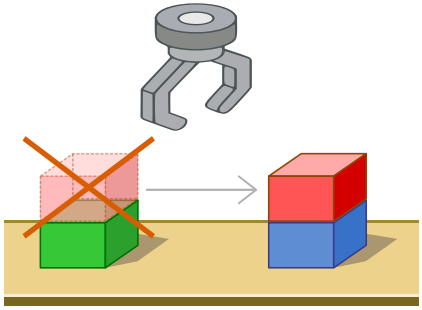

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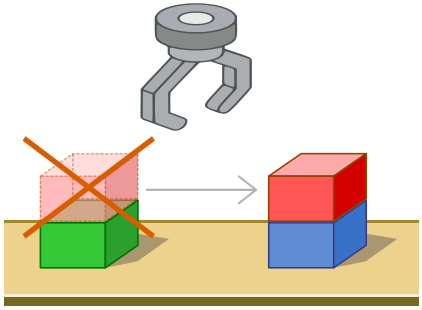

- Easier to model planning problems with fully ontology-aware semantics

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Coherent eKAB (ceKAB) task: $(\mathcal{P}, \mathcal{A}, \mathcal{T}, \mathcal{O}, I, G)$

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There is a polynomial compilation scheme from DL-Lite ceKABs into PDDL with derived predicates that preserves plan length with a factor of 2.

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- Plan existence for ceKABs is ExpSpace-complete

KR'25 experiments

- implementation of compilation using $\mathcal{R}_{Add,Del}$
- use Nemo to saturate $\mathcal{T}$ (Ivliev, Gerlach, Meusel, Steinberg, and Krötzsch 2024)

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  - 35 new DL-Lite tasks (Blocks)

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  - 125 previous DL-Lite eKAB tasks, slightly modified for new semantics
  - 35 new DL-Lite tasks (Blocks)
- compare to eKABs (B, Hoffmann, Kovtunova, Krötzsch, Nebel, and Steinmetz 2022)

KR'25 results

Domain	#	# solved AAAI22	# solved KR25	planning time (s) AAAI22	planning time (s) KR25
Cats*	20	20	20	32.37	0.01
Elevator	20	20	20	51.73	0.02
Robot*	20	20	18	0.03	60.17
TaskAssign	20	20	20	0.11	0.32
TPSA	15	15	15	0.95	1.03
VTA	15	15	14	2.64	3.64
VTA-Roles	15	15	14	2.66	3.82
Blocks	35	35	35	3.00	0.98
Overall	**160**	**160**	**156**	12.04	7.97

not much worse than eKAB semantics

much more expressive

sensitive to planning heuristics

Summary

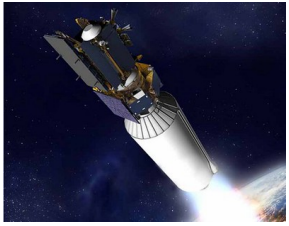
- practical compilations for planning with ontologies
- for DL-Lite and Horn DLs
- limits of compilability (Horn-$\mathcal{ALCHOIQ}$ vs. Horn-$\mathcal{SROIQ}$)

Summary

- practical compilations for planning with ontologies
- for DL-Lite and Horn DLs
- limits of compilability (Horn-$\mathcal{ALCHOIQ}$ vs. Horn-$\mathcal{SROIQ}$)

Future work:

- coherent updates beyond DL-Lite
- non-Horn languages ($\texttt{on} \sqsubseteq \texttt{onblock} \sqcup \texttt{ontable}$, $\texttt{on}$ is acyclic) (John and Koopmann 2024)
- temporal ontologies and goals



Collaborators


Jörg Hoffmann


Marcel Steinmetz


Bernhard Nebel


Alisa Kovtunova


Markus Krötzsch


Duy Nhu


Gabriele Röger

UNIVERSITÄT DES SAARLANDES

UNI FREIBURG

Dresden University of Technology

Universität Basel

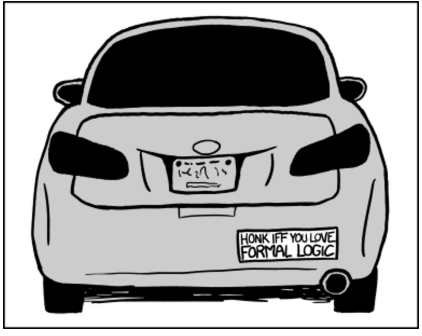
CPEC CENTER FOR PERSPICUOUS COMPUTING

DFG Deutsche Forschungsgemeinschaft German Research Foundation

Swiss National Science Foundation

Thank you!

Questions?



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