Counting and Reasoning with Plans

David Speck[1] Markus Hecher[2] Daniel Gnad[3]
Johannes Fichte[3] Augusto Corrêa[4]

[1] University of Basel [2] Université d'Artois, CNRS, CRIL
[3] Linköping University [4] University of Oxford

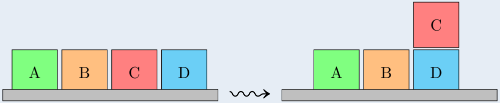
AAAI'25, February 28, 2024

Motivation

Motivation

What is Classical Planning?

- Given: State and a Goal
- Objective: find a plan
  (a sequence of operators)



Today's Limitations

- Focus on single plan, single preferred/optimal plan
- Counting plans, partial enumeration
- Understanding plan space fairly unstudied

Motivation (cont.)

Aim

- Bridge the gap between counting and classical planning
- More fine grained perspective on plan space

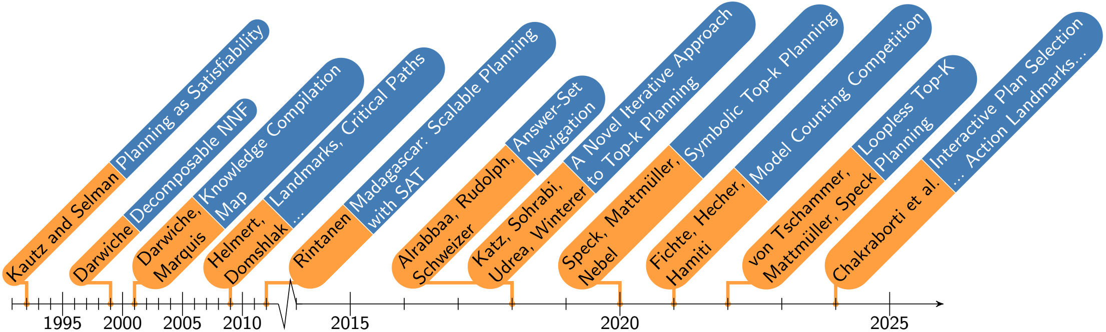
Main Contributions (tldr)

- Framework for reasoning and analyzing plan space (more fine grained reasoning)
- Taxonomy of counting and reasoning problems for classical planning
- Practical tool: `Planalyst`

Related Works & Background

Related Works

Selection:



+ Works in Knowledge Representation and Reasoning (Probabilistic Planning, Sampling, ASP Navigation, SAT/ASP Enumeration, Model Counters)

Background

Planning Task

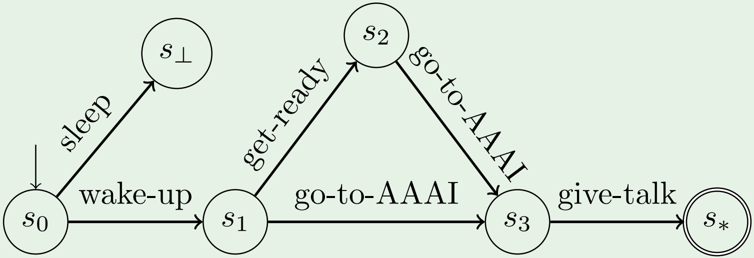
- Task $\Pi = \langle \mathcal{A}, \mathcal{O}, \mathcal{I}, \mathcal{G} \rangle$ where
  - $\mathcal{A}$: finite set of propositional state variables.
  - $\mathcal{O}$ finite set of operators (preconditions and effects)
  - $\mathcal{I}$: initial state of Π
  - $\mathcal{G}$: goal condition
- State s is a mapping $s : \mathcal{A} \to \{0, 1\}$ and Goal state if $s_* \models \mathcal{G}$.

Plan

- Sequence $\pi = \langle o_0, \ldots, o_{n-1} \rangle$ is a of applicable operators
- Generates a sequence of states $s_0, \ldots, s_n$, where $s_0 = \mathcal{I}$, s_n is a goal state
- Assumption: Poly-bounded plan length

Background (cont.)

Example 1 (Chaotic Researcher giving AAAI Talk)



State space. The initial state s_0; the goal state s_*.

Qualitative to Quantitative Reasoning

Decision Reasoning Modes

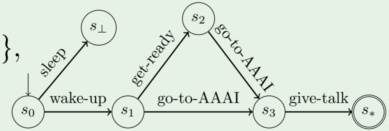
Definition

Planning task Π and an length ℓ

- Brave operators: used by at least one plan $\mathcal{BO}_\ell(\Pi) := \bigcup_{\pi \in \mathsf{Plans}_\ell(\Pi)} \nabla(\pi)$
- Cautious operators: used in all plans (landmark) $\mathcal{CO}_\ell(\Pi) := \bigcap_{\pi \in \mathsf{Plans}_\ell(\Pi)} \nabla(\pi)$
  (c.f., (Zhu and Givan2003)) $\nabla(\cdot)\colon (v_1, \ldots, v_n) \rightsquigarrow \{v_1, \ldots, v_n\}$

Example 2

$\mathcal{BO}_\ell(\Pi_1) = \{\text{wake-up, get-ready, go-to-AAAI, give-talk}\}$,
$\mathcal{CO}_\ell(\Pi_1) = \{\text{wake-up, go-to-AAAI, give-talk}\}$.



Faceted Reasoning

Operators that allow for flexibility / uncertainty

- Inclusive facets: $\mathcal{F}_\ell^+(\Pi) := \mathcal{BO}_\ell(\Pi) \setminus \mathcal{CO}_\ell(\Pi)$ (enforce on plan)
- Excluding facets: $\mathcal{F}_\ell^- := \{ \neg o \mid o \in \mathcal{F}^+(\Pi) \}$ (forbid from plan)
- Significance of operator o:

$$\mathbb{S}_\ell(\Pi, o) := \frac{|\mathcal{F}_\ell(\Pi)| - |\mathcal{F}_\ell(\Pi[o])|}{|\mathcal{F}_\ell(\Pi)|}$$

Quantitative Reasoning Modes

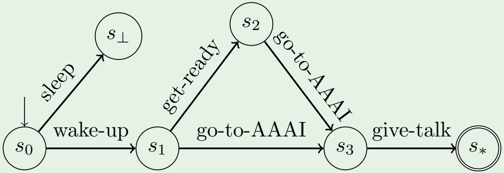
Probability Reasoning

- Conditional probability: $\mathbb{P}_\ell[\Pi, o] := \dfrac{|\mathsf{Plans}_\ell(\Pi, o)|}{\max(1, |\mathsf{Plans}_\ell(\Pi)|)}$
- Query Q: states, operators, states and operators in position i
  $\mathsf{Plans}_\ell(\Pi, Q) := \{\, \pi \mid \pi \in \mathsf{Plans}_\ell(\Pi), \pi \models Q \,\}$.
- Exact Probability Reasoning: asks if $\mathbb{P}_\ell[\Pi, Q] = p$

brave	*probability*	cautious
$0 < p \leq 1$	$p \in [0, 1]$	$p = 1$

Quantitative Reasoning Modes (cont.)

Example 3 (Queries)



Simple Queries:

(i) $\mathbb{P}_\ell[\Pi_1, \text{wake-up}] = 1$, (ii) $\mathbb{P}_\ell[\Pi_1, \text{get-ready}] = 0.5$, (iii) $\mathbb{P}_\ell[\Pi_1, \text{sleep}] = 0$.

Complex Queries:

(i) $\mathbb{P}_\ell[\Pi_1, \text{wake-up} \wedge \text{sleep}] = 0$, (ii) $\mathbb{P}_\ell[\Pi_1, \text{wake-up} \vee \text{sleep}] = 1$.

Complexity Classification

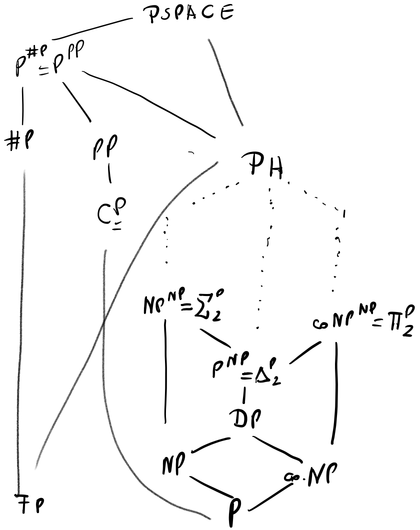
Computational Complexity

Background

- $\#\mathrm{P}$: counting counter part of NP, i.e., problems solved by counting accepting paths of a nondeterministic TM (Valiant1979)
- DP: (independent) combination of an NP and a coNP problem, i.e., $\mathrm{DP} := \{ L_1 \cap L_2 \mid L_1 \in \mathrm{NP}, L_2 \in \mathrm{coNP} \}$ (Papadimitriou and Yannakakis1982)
- PP: decision problems solved by nondeterministic TM, s.t. positive instances are those where at least 1/2 of the machine's paths are accepting (Gill1977)
- $\mathrm{C}_{=}^{\mathrm{P}}$: decision problems solved by nondeterministic TM where positive instances are those with the same number of accepting and rejecting paths (Fenner et al.1999)

Comprehensive Complexity Classification

Name	Task	Compl.
Poly-Bounded-Plan-Exist	$\pi \in \mathsf{Plans}_\ell(\Pi)$	NP-c
#Poly-Bounded-Plan	$\lvert\mathsf{Plans}_\ell\rvert$	#P-c
Poly-Bounded-Top-k-Exist	$\lvert\mathsf{Plans}_\ell\rvert \geqslant k$	PP-h
Poly-Brave-Plan-Exist	$\exists \pi \in \mathsf{Plans}_\ell(\Pi) : o \in \pi$	NP-c
Poly-Cautious-Plan-Exist	$\forall \pi \in \mathsf{Plans}_\ell(\Pi) : o \in \pi$	coNP-c
Poly-Probabilistic-Reason	$\mathbb{P}_\ell[\Pi, Q] = p$	$\mathrm{C}_{=}^{\mathrm{P}}$-c
FacetReason	$o \in \mathcal{F}_\ell(\Pi)$	NP-c
AtLeast-k-Facets	$\lvert\mathcal{F}_\ell(\Pi)\rvert \geqslant k$	NP-c
AtMost-k-Facets	$\lvert\mathcal{F}_\ell(\Pi)\rvert \leqslant k$	coNP-c
Exact-k-Facets	$\lvert\mathcal{F}_\ell(\Pi)\rvert = k$	DP-c



Empirical Evaluation

Empirical Evaluation

- `Planalyst`: Counting using KC (`d4`) (Lagniez and Marquis2017)
- Competitive: with top-k planners; instance sets: 31
- Outperforms: large space (>10 Mio)

Domains	Bound: ×1				Bound: ×1.5			
	K*	SymK	Enum	Count	K*	SymK	Enum	Count
airport (49)	7	7	7	**11**	7	7	6	**11**
blocks (35)	28	31	29	**33**	9	8	7	**15**
logistics (63)	9	6	4	**13**	1	1	0	**3**
miconic (150)	**39**	35	31	**39**	14	13	10	**24**
mystery (19)	**16**	14	14	15	**11**	8	7	9
psr-small (50)	46	44	41	**48**	14	14	8	**24**
...	...	...	...	...	...	...	...	...
Sum (1094)	**351**	309	253	335	112	91	61	**170**

Conclusion

Summary and Future Works

Conclusion

- Orthogonal to previous works in planning
- Reason about plan space (queries, facets, significance)
- Reasoning tool `Planalyst`

Future Works

- Practical reasoning with facets
- Integrate `Planalyst` into existing pipelines (goal recognition, rewriting)
- Explaining decisions, inconsistencies, certifying results

Summary and Future Works

Conclusion

- Orthogonal to previous works in planning
- Reason about plan space (queries, facets, significance)
- Reasoning tool `Planalyst`

Future Works

- Practical reasoning with facets
- Integrate `Planalyst` into existing pipelines (goal recognition, rewriting)
- Explaining decisions, inconsistencies, certifying results

Thanks for listening. Qs?

Research supported by FWF, ÖAW, WWTF, ELLIIT.

References I

Christian Alrabbaa, Sebastian Rudolph, and Lukas Schweizer. Faceted answer-set navigation. In Proc. RuleML+RR 2018, pages 211–225, 2018.

Tom Bylander. The computational complexity of propositional STRIPS planning. AIJ, 69(1–2):165–204, 1994.

Tathagata Chakraborti, Jungkoo Kang, Francesco Fuggitti, Michael Katz, and Shirin Sohrabi. Interactive plan selection using linear temporal logic, disjunctive action landmarks, and natural language instruction. In Proc. AAAI 2024, pages 23775–23777, 2024.

Adnan Darwiche. Compiling knowledge into decomposable negation normal form. In Proc. IJCAI 1999, pages 284–289, 1999.

Adnan Darwiche and Pierre Marquis. A knowledge compilation map. JAIR, 17: 229–264, 2002.

References II

Stephen A. Fenner, Frederic Green, Steven Homer, and Randall Pruim. Determining acceptance possibility for a quantum computation is hard for the polynomial hierarchy. ECCC, TR99-003, 1999.

Johannes K. Fichte, Markus Hecher, and Florim Hamiti. The model counting competition 2020. ACM Journal of Experimental Algorithmics, 26(13):1–26, 2021.

John Gill. Computational complexity of probabilistic turing machines. SICOMP, 6(4): 675–695, 1977.

Malte Helmert and Carmel Domshlak. Landmarks, critical paths and abstractions: What's the difference anyway? In Proc. ICAPS 2009, pages 162–169, 2009.

Michael Katz, Shirin Sohrabi, Octavian Udrea, and Dominik Winterer. A novel iterative approach to top-k planning. In Proc. ICAPS 2018, pages 132–140, 2018.

Henry Kautz and Bart Selman. Planning as satisfiability. In Proc. ECAI 1992, pages 359–363, 1992.

References III

Jean-Marie Lagniez and Pierre Marquis. An improved decision-DNNF compiler. In Proc. IJCAI 2017, pages 667–673, 2017.

Christos H. Papadimitriou and Mihalis Yannakakis. The complexity of facets (and some facets of complexity). In Proc. STOC 1982, pages 255–260, 1982.

Jussi Rintanen. Madagascar: Scalable planning with SAT. In IPC 2011 Planner Abstracts, pages 61–64, 2011.

David Speck, Robert Mattmüller, and Bernhard Nebel. Symbolic top-k planning. In Proc. AAAI 2020, pages 9967–9974, 2020.

Leslie G. Valiant. The complexity of computing the permanent. Theoretical Computer Science, 8:189–201, 1979.

Julian von Tschammer, Robert Mattmüller, and David Speck. Loopless top-k planning. In Proc. ICAPS 2022, pages 380–384, 2022.

Lin Zhu and Robert Givan. Landmark extraction via planning graph propagation. In ICAPS 2003 Doctoral Consortium, pages 156–160, 2003.

Comprehensive Complexity Classification

Name	Given	Task	Compl.	Ref.
POLY-BOUNDED-PLAN-EXIST	Π, ℓ	$\pi \in \text{Plans}_\ell(\Pi)$	NP-c	[1]
POLY-BRAVE-PLAN-EXIST	Π, ℓ, o	$\exists\pi \in \text{Plans}_\ell(\Pi) : o \in \pi$	NP-c	Lem. 6
POLY-CAUTIOUS-PLAN-EXIST	Π, ℓ, o	$\forall\pi \in \text{Plans}_\ell(\Pi) : o \in \pi$	coNP-c	Lem. 6
POLY-BOUNDED-TOP-K-EXIST	Π, ℓ	$\|\text{Plans}_\ell\| \geqslant k$	PP-h	[2]
#POLY-BOUNDED-PLAN	Π, ℓ	$\|\text{Plans}_\ell\|$	#P-c	[2]
POLY-PROBABILISTIC-REASON	Π, ℓ, Q, p	$\mathbb{P}_\ell[\Pi, Q] = p$	$\text{C}^{\text{P}}_{=}$-c	Thm. 9
FACETREASON	Π, ℓ, o	$o \in \mathcal{F}_\ell(\Pi)$	NP-c	Thm. 10
ATLEAST-K-FACETS	Π, ℓ, k	$\|\mathcal{F}_\ell(\Pi)\| \geqslant k$	NP-c	Lem. 11
ATMOST-K-FACETS	Π, ℓ, k	$\|\mathcal{F}_\ell(\Pi)\| \leqslant k$	coNP-c	Cor. 12
EXACT-K-FACETS	Π, ℓ, k	$\|\mathcal{F}_\ell(\Pi)\| = k$	DP-c	Thm. 13

Computational Complexity of Qualitative and Quantitative Reasoning Problems.

Π planning task, $\ell \in \mathbb{N}_0$ with $\ell \leqslant poly(\Pi)$, $o \in \mathcal{O}$, $k \in \mathbb{N}_o$, $0 \leqslant p \leqslant 1$, and Q a query.

[1]: (Bylander1994), [2]: (Speck et al.2020).