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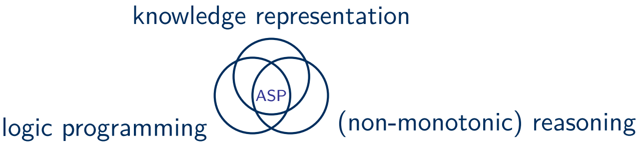
Navigating and Querying Answer Sets: How Hard Is It Really and Why?

joint work with: Dominik Rusovac, Markus Hecher, Martin Gebser, and Johannes K Fichte

Hanoi, 7th November 2024

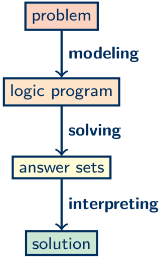
Answer Set Programming (ASP)



Declarative problem solving

- planning
- product configuration
- diagnosis

⋮



ASP Modelling and Solving

```
#const n=14.
{q(I, 1..n)} == 1 :- I = 1..n.
{q(1..n, J)} == 1 :- J = 1..n.
:- {q(D-J,J)} >=2, D=2..2*n.
:- {q(D+J,J)} >=2, D=1-n..n-1.
```

solver →

```
Answer: 1
q(5,13) q(7,14) q(2,8) q(6,11) q(4,7) q(1,3) q(9,10)
q(12,12) q(3,2) q(8,5) q(10,6) q(14,9) q(11,4) q(13,1)
Answer: 2
q(2,12) q(1,9) q(7,13) q(6,11) q(4,7) q(12,14) q(9,10)
q(3,3) q(5,4) q(8,5) q(10,6) q(14,8) q(11,1) q(13,2)
Answer: 3
q(1,13) q(7,14) q(3,9) q(6,11) q(4,7) q(2,4) q(9,10)
q(12,12) q(5,3) q(10,6) q(14,8) q(8,1) q(13,5) q(11,2)
⋮
Answer: 365596
q(4,13) q(1,9) q(7,14) q(3,8) q(2,6) q(8,11) q(11,12)
q(5,4) q(12,10) q(9,5) q(6,1) q(13,7) q(10,3) q(14,2)
SATISFIABLE
```

Navigating ASP Solution Spaces

```
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{q(1..n, J)} == 1 :- J = 1..n.
:- {q(D-J,J)} >=2, D=2..2*n.
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Diverse Solutions:

```
Solution: 1
q(1,12) q(2,8) q(3,6) q(4,14) q(5,9) q(6,2) q(7,5)
q(14,1) q(9,11) q(10,7) q(11,10) q(12,4) q(13,13) q(8,3)
Solution: 2
q(1,1) q(2,10) q(3,5) q(4,7) q(5,12) q(6,3) q(7,11)
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Solution: 3
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```

Quantitative Reasoning:

* zoom in
* zoom out
* ...

Visual Approach:

* zoom in
* zoom out
* ...

Weighted Faceted Answer Set Navigation

[1] Johannes Klaus Fichte, Sarah Alice Gaggl, Dominik Rusovac. **Rushing and Strolling among Answer Sets - Navigation Made Easy**
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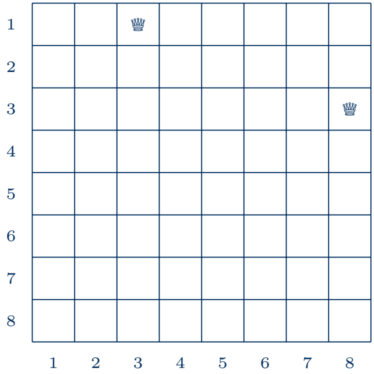
	2		5		1		9	
8			2		3			6
	3			6			7	
		1						
5	4						1	9
						7		
	9			3			8	
2			8		4			7
	1		9		7		6	

How to solve this Sudoku as quick as possible?



Which moves (queens) have the least/most impact?

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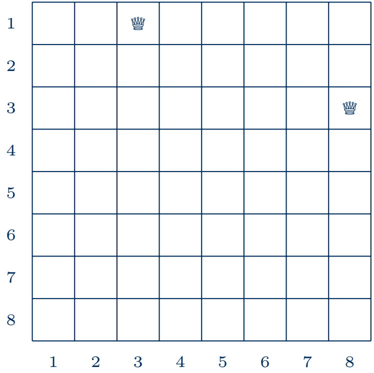

Which moves (queens) have the least/most impact?

How can we find answers without going through all solutions?

Outline

– Preliminaries
– Weighted Faceted Navigation
– Complexity Results for Facet Reasoning
– Querying Answer Sets
– Conclusion

Preliminaries

Definition (logic program)

A (normal disjunctive) *logic program* Π over a set of atoms $\{\alpha_0, \dots, \alpha_n\}$ is a finite set of rules r of the form:

$$\alpha_0 \,|\, \dots \,|\, \alpha_k \leftarrow \alpha_{k+1}, \dots, \alpha_m, {\sim}\alpha_{m+1}, \dots, {\sim}\alpha_n. \text{ where } 0 \leq k \leq m \leq n$$

Remark: We focus on ground programs without extended rules.

$\mathcal{AS}(\Pi) \dots$ **answer sets** (solutions)

$2^{\mathcal{AS}(\Pi)} \dots$ **solution space**

$\mathcal{BC}(\Pi) \coloneqq \bigcup \mathcal{AS}(\Pi) \dots$ **brave consequences**

$\alpha \in \mathcal{BC}(\Pi) \dots$ **partial solution**

$\mathcal{CC}(\Pi) \coloneqq \bigcap \mathcal{AS}(\Pi) \dots$ **cautious consequences**

Part 1 Weighted Faceted Navigation

Systematic Faceted Navigation

$\Pi : \quad a \,|\, b. \quad c \,|\, d \leftarrow b. \quad e.$

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Facets: $\mathcal{F}(\Pi) = \{a, b, c, d, \overline{a}, \overline{b}, \overline{c}, \overline{d}\}$

`ANSWER 1:` a, e

`ANSWER 2:` b, c, e

`ANSWER 3:` b, d, e

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Facets: $\mathcal{F}(\Pi) \coloneqq \underbrace{\{a, b, c, d\}}_{\mathcal{F}^+(\Pi) \coloneqq \mathcal{BC}(\Pi) \setminus \mathcal{CC}(\Pi)} \cup \underbrace{\{\overline{a}, \overline{b}, \overline{c}, \overline{d}\}}_{\mathcal{F}^-(\Pi) \coloneqq \{\overline{\alpha} \mid \alpha \in \mathcal{F}^+(\Pi)\}}$

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Routes: $\Delta^{\Pi} \coloneqq \{\langle f_0, \ldots, f_n \rangle \mid f_i \in \mathcal{F}(\Pi), 0 \leq i \leq n\} \cup \{\epsilon\}$

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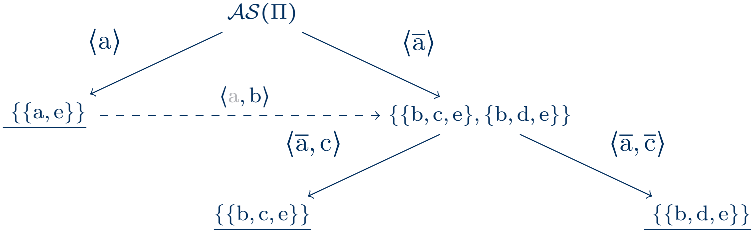

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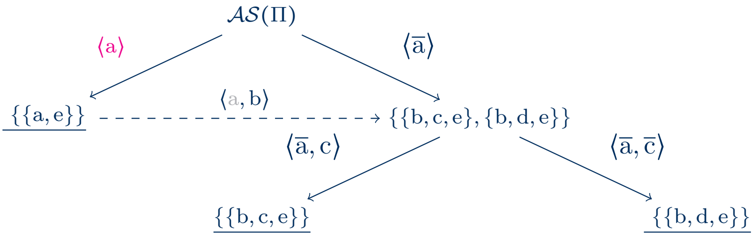

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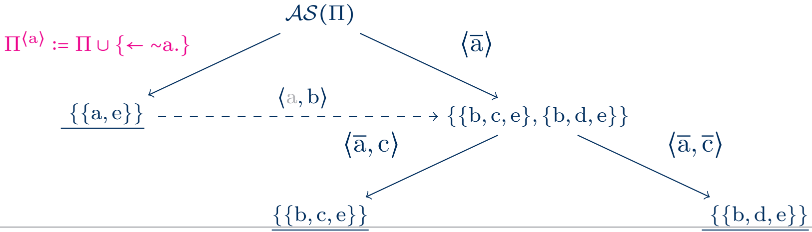

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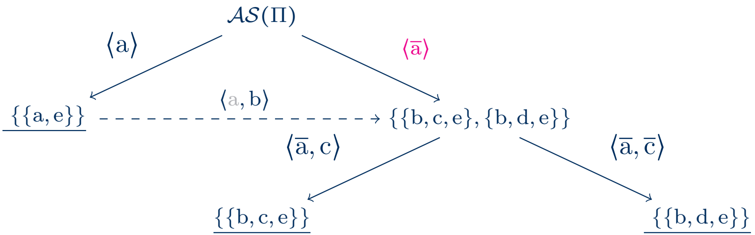

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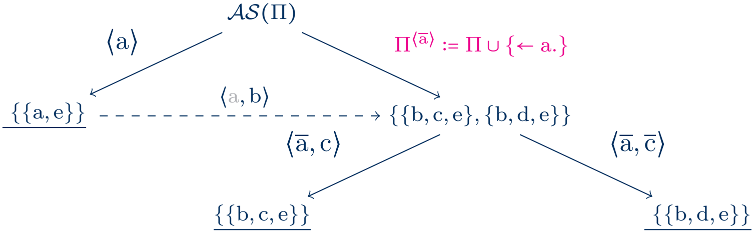
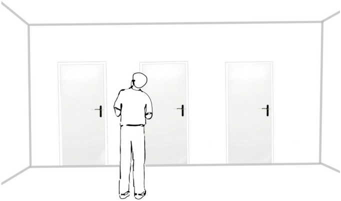


What is the effect of taking a certain navigation step?

Can we somehow characterize sub-spaces beforehand?



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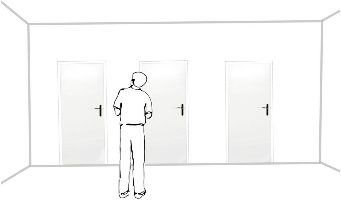

Let's do some counting!

Quantifying effects of navigation steps

The Weight of a Facet

Definition (weighting function)

We call $\# : \{\Pi^\delta \mid \delta \in \Delta^\Pi\} \to \mathbb{N}$ *weighting function*, whenever $\#(\Pi^\delta) > 0$, if $|\mathcal{AS}(\Pi)| \geq 2$.

Definition (weight)

Let $\delta \in \Delta^\Pi$, $\mathrm{f} \in \mathcal{F}(\Pi)$ and δ' be a redirection of δ w.r.t. f. The *weight* of f w.r.t. $\#$, Π^δ and δ' is defined as:

$$\omega_\#(\mathrm{f}, \Pi^\delta, \delta') \coloneqq \begin{cases} \#(\Pi^\delta) - \#(\Pi^{\delta'}), & \text{if } \langle \delta, \mathrm{f} \rangle \notin \Delta^\Pi_\mathrm{s} \text{ and } \delta' \neq \epsilon; \\ \#(\Pi^\delta) - \#(\Pi^{\langle \delta, \mathrm{f} \rangle}), & \text{otherwise.} \end{cases}$$

Facet Counting Weight

Count Facets with $\omega_{\#_\mathcal{F}}$

- $\omega_{\#_\mathcal{F}}$ provides information on the similarity/diversity of solutions
- Outputting the facet-counting weight $\omega_{\#_\mathcal{F}}$ for a given program Π and route δ is in Δ_3^{P}[1]
- Precise computational complexity of facet problems remained widely open

$$\mathcal{AS}(\Pi) = \{\{\mathrm{a}, \mathrm{e}\}, \{\mathrm{b}, \mathrm{c}, \mathrm{e}\}, \{\mathrm{b}, \mathrm{d}, \mathrm{e}\}\}$$

$$\omega_{\#\mathcal{F}}(\mathrm{b}, \Pi, \epsilon) = 4 \quad \downarrow$$

$$\mathcal{AS}(\Pi^{\langle \mathrm{b} \rangle}) = \{\{\mathrm{b}, \mathrm{c}, \mathrm{e}\}, \{\mathrm{b}, \mathrm{d}, \mathrm{e}\}\}$$

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$$\omega_{\#\mathcal{F}}(\overline{\mathrm{c}}, \Pi, \epsilon) = 2 \quad \downarrow$$

$$\mathcal{AS}(\Pi^{\langle \overline{\mathrm{c}} \rangle}) = \{\{\mathrm{a}, \mathrm{e}\}, \{\mathrm{b}, \mathrm{d}, \mathrm{e}\}\}$$

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Rushing and Strolling among Answer Sets

Definition (strictly goal-oriented navigation mode)

The *stricly goal-oriented* navigation mode $\nu^{\#}_{\mathrm{sgo}} : \Delta^{\Pi}_{\mathrm{s}} \times \mathcal{F}(\Pi) \to 2^{\mathcal{AS}(\Pi)}$ is defined by:

$$\nu^{\#}_{\mathrm{sgo}}(\delta, \mathrm{f}) := \begin{cases} \mathcal{AS}(\Pi^{\langle \delta, \mathrm{f} \rangle}), & \text{if } \mathrm{f} \in \max_{\omega_{\#}}(\Pi^{\delta}); \\ \mathcal{AS}(\Pi^{\delta}), & \text{otherwise.} \end{cases}$$

Definition (explore navigation mode)

The *explore* navigation mode $\nu^{\#}_{\mathrm{expl}} : \Delta^{\Pi}_{\mathrm{s}} \times \mathcal{F}(\Pi) \to 2^{\mathcal{AS}(\Pi)}$ is defined by:

$$\nu^{\#}_{\mathrm{expl}}(\delta, \mathrm{f}) := \begin{cases} \mathcal{AS}(\Pi^{\langle \delta, \mathrm{f} \rangle}), & \text{if } \mathrm{f} \in \min_{\omega_{\#}}(\Pi^{\delta}); \\ \mathcal{AS}(\Pi^{\delta}), & \text{otherwise.} \end{cases}$$

Part 2 Complexity Results for Facet Reasoning

Complexity Results

Problem	Given	Task	**Disj**	**Tight/Normal**	Reference
AspFacetReason	Π, $a \in at(\Pi)$	$a \in \mathcal{F}(\Pi)$	Σ_2^P-c	NP-c	Theorem 4
Exact-k-Facets	Π, $k \in \mathbb{N}_0$	$\lvert\mathcal{F}(\Pi)\rvert = k$	D_2^P-c	D_1^P-c	Theorem 7
AtLeast-k-Facets	Π, $k \in \mathbb{N}_0$	$\lvert\mathcal{F}(\Pi)\rvert \geq k$	Σ_2^P-c	NP-c	Corollary 8
AtMost-k-Facets	Π, $k \in \mathbb{N}_0$	$\lvert\mathcal{F}(\Pi)\rvert \leq k$	Π_2^P-c	NP-c	Corollary 9
FacetNumCompare	Π_1, Π_2	$\lvert\mathcal{F}(\Pi_1)\rvert > \lvert\mathcal{F}(\Pi_2)\rvert$	Θ_3^P-c	Θ_2^P-c	Theorem 10

Part 3 Querying Answer Sets

Querying Solution Spaces

- Propositional queries to select answer sets matching specific conditions
- Program Π, prop. formula F, answer sets of Π that satisfy F
  $\sigma_F(\Pi) := \{M \in \mathcal{AS}(\Pi) \mid M \models F\}$
- Express propositional query itself in ASP

Example

$$\Pi_1 = \{p \leftarrow {\sim}q;\ q \leftarrow {\sim}p;\ r \vee s \leftarrow q;\ t \leftarrow \}.$$

The answer sets of Π_1 are $\mathcal{AS}(\Pi_1) = \{\{p,t\}, \{q,r,t\}, \{q,s,t\}\}$, and $\mathcal{F}(\Pi_1) = \{p,q,r,s\}$.

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Query for $F = (\neg r \wedge s) \vee (p \wedge \neg q)$?

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Query for $F = (\neg r \wedge s) \vee (p \wedge \neg q)$?

$$\sigma_{(\neg r \wedge s) \vee (p \wedge \neg q)}(\Pi_1) = \{\{p,t\},\{q,s,t\}\}$$

Matching all Elements

Terms

$$\sigma_{\bigwedge_{\ell \in \mathrm{L}} \ell}(\Pi) = \mathcal{AS}(\Pi \cup \{\leftarrow \sim\ell \mid \ell \in \mathrm{L}\})$$

Π program, L set of literals

Matching all Elements

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$\Pi_1 = \{p \leftarrow {\sim}q;\ q \leftarrow {\sim}p;\ r \vee s \leftarrow q;\ t \leftarrow\ \}$, $\mathcal{AS}(\Pi_1) = \{\{p, t\}, \{q, r, t\}, \{q, s, t\}\}$

$$\sigma_{p \wedge \neg q}(\Pi_1) = \mathcal{AS}(\Pi_1 \cup \{\leftarrow {\sim}p;\ \leftarrow q\}) = \{\{p, t\}\}$$

Matching at least one Element

Clauses

$$\sigma_{\bigvee_{\ell \in \mathrm{L}} \ell}(\Pi) = \mathcal{AS}(\Pi \cup \{\leftarrow \sim\mathrm{L}\})$$

Π program, L set of literals, $\sim\mathrm{L} \coloneqq \{\sim\ell \mid \ell \in \mathrm{L}\}$

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$$\sigma_{s \vee \neg q}(\Pi_1) = \mathcal{AS}(\Pi_1 \cup \{\leftarrow \sim s, q\}) = \{\{p, t\}, \{q, s, t\}\}$$

Matching CNFs

CNFs

$$\sigma_F(\Pi) = \mathcal{AS}(\Pi \cup \{\leftarrow {\sim}L_i \mid L_i \in F\})$$

Π program, L set of literals, F a simple formula in CNF, $F = \{L_1, \ldots, L_m\}$ set of clauses

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$$\sigma_{(p \vee \neg q) \wedge (\neg s \vee r)}(\Pi_1) = \mathcal{AS}(\Pi_1 \cup \{\leftarrow {\sim}p, q;\ \leftarrow s, {\sim}r\}) = \{\{p,t\}, \{q,r,t\}\}$$

Matching DNFs

DNFs

$$\sigma_F(\Pi) = \{M \setminus \{a_1, \dots, a_m\} \mid M \in \mathcal{AS}(\Pi \cup \{a_i \leftarrow {\sim}\ell \mid 1 \leq i \leq m, \ell \in L_i\} \cup \{\leftarrow a_1, \dots, a_m\})\}$$

where $a_1, \dots, a_m$ are fresh atoms

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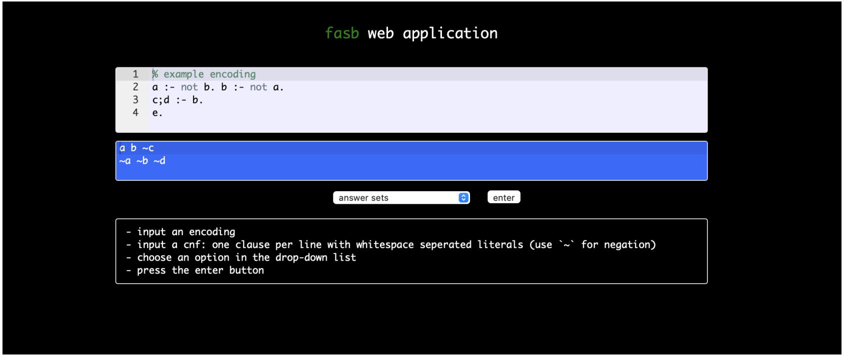
$$\begin{aligned}\sigma_{(\neg r \wedge s) \vee (p \wedge \neg q)}(\Pi_1) &= \{M \setminus \{a_1, a_2\} \mid M \in \mathcal{AS}(\Pi_1 \cup \{a_1 \leftarrow r;\ a_1 \leftarrow \sim s;\ a_2 \leftarrow \sim p;\ a_2 \leftarrow q;\ \leftarrow a_1, a_2\})\} \\ &= \{\{p,t\}, \{q,s,t\}\}\end{aligned}$$

fasb – Faceted Answer Set Browser

REPL on top of clingo solver implementing: $\nu_{\mathrm{go}}, \nu^{\#}_{\mathrm{sgo}}, \nu^{\#}_{\mathrm{expl}}$ for $\# \in \{\#_{\mathcal{AS}}, \#_{\mathcal{F}}\}$

https://github.com/drwadu/fasb



https://drwadu.github.io/web-fasb.github.io/

Summary & Future Work

Summary:

- Weighted faceted navigation allows to quantitatively explore the solution space
- Complexity results for facet reasoning
- Empirical evaluation of facet reasoning (in paper)
- Extend facet reasoning to queries on ASP solution spaces

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Future Work:

- We expect facet reasoning to be of interest for various formalisms in KR and AI (QBFs, planning, argumentation, DL, epistemic logic programming, constraint programming and paraconsistent reasoning
- Characterise practical applications for facet reasoning, while approximate or exact solution counting would be required otherwise
- Investigate the complexity of facets in the presence of preferences

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Dominik Rusovac

Markus Hecher

Martin Gebser

Johannes Fichte

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