TECHNISCHE UNIVERSITÄT DRESDEN

NAVAS CPEC CENTER FOR PERSPICUOUS COMPUTING

Sarah Gaggl
LPArg Group

Scalable Understanding

Navigation Approaches for Answer Sets

online, 20th October 2022

Motivation
Searching for the Right Bicycle

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Motivation
Combinatorial Search Problems

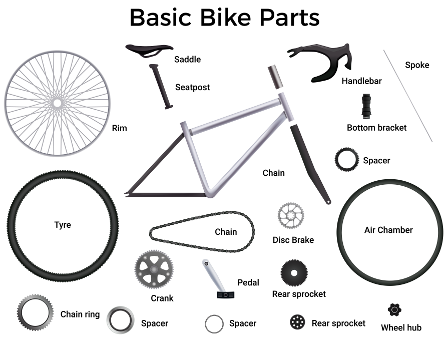
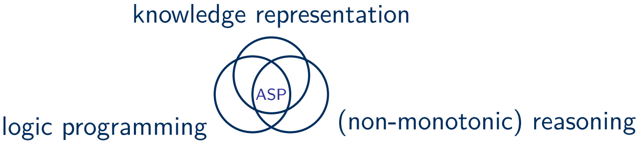


Figure 1: Bunt Vektor erstellt von macrovector - de.freepik.com

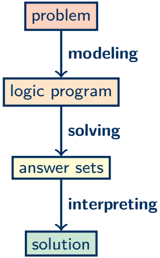
Answer Set Programming (ASP)



Declarative problem solving

- planning
- product configuration

⋮



The NAVAS Project
Navigation Approaches for Answer Sets

BMBF fundet project 10/2020 – 09/2024

Goals

Allow for an interactive navigation within the ASP solution space by

1. Development of methods to navigate within the ASP solution space
2. Prototypical implementation of those methods with efficient algorithms
3. Evaluation on use cases *configuration* and *argumentation*

Team:

PI Sarah Gaggl

Elisa Böhl

Dominik Rusovac

Outline

- Preliminaries
- Weighted Faceted Navigation
- Incremental Answer Set Counting
- Diverse Answer Sets
- Visual Approach for Solution Space Exploration
- Conclusion

Preliminaries

Definition (logic program)

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

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

Remark: We focus on ground programs without extended rules.

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

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

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

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

$\mathcal{CC}(\Pi) \coloneqq \bigcap \mathcal{AS}(\Pi) \ldots$ **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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$\Pi: \quad a \,|\, b. \quad c \,|\, d \leftarrow b. \quad e.$

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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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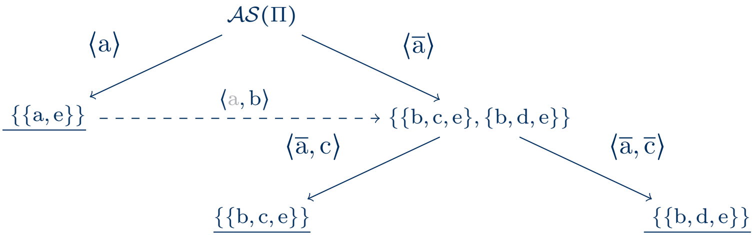

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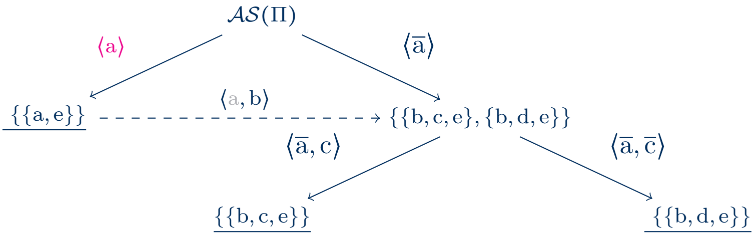

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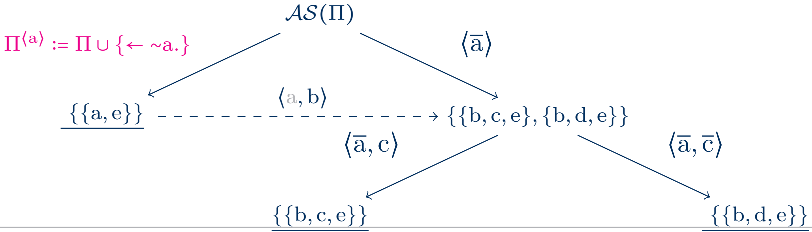

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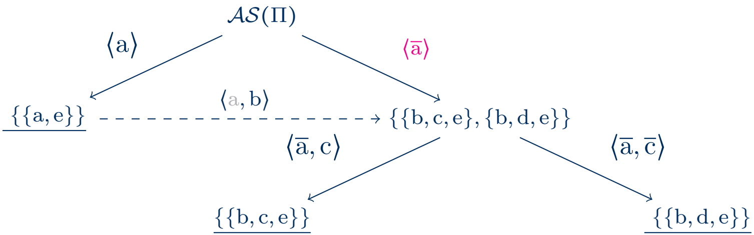

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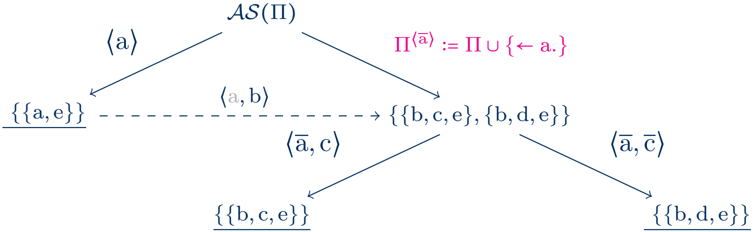
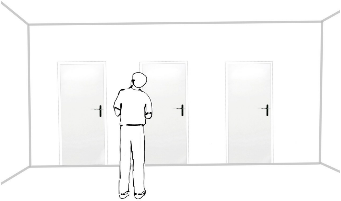


What is the effect of taking a certain navigation step?

Can we somehow characterize sub-spaces beforehand?



[1] Johannes Klaus Fichte, SAG, Dominik Rusovac. **Rushing and Strolling among Answer Sets - Navigation Made Easy**
Proceedings of the 36th AAAI Conference on Artificial Intelligence (AAAI 2022), 2022.

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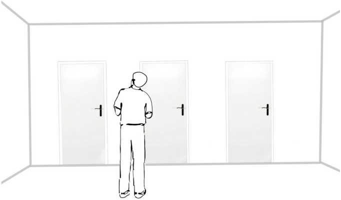

Let's do some counting!

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:

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

The Weight of a Facet

Definition (weight)

Let $\delta \in \Delta^{\Pi}$, $f \in \mathcal{F}(\Pi)$ 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:

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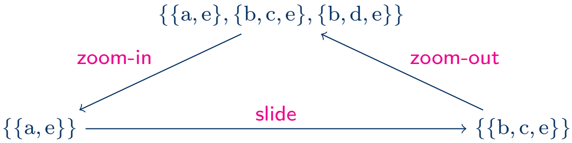
Effects:



Which Weighting Function? Absolute vs. Relative Weights

Natural choice?

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Natural choice?

- Absolute Weight:
  Count Answer Sets with $\omega_{\#_{\mathcal{AS}}}$

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

$$\omega_{\#\mathcal{AS}}(b, \Pi, \epsilon) = 1 \downarrow$$

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

Which Weighting Function? Absolute vs. Relative Weights

Natural choice?

- Absolute Weight:
  Count Answer Sets with $\omega_{\#_{\mathcal{AS}}}$

  Counting answer sets is hard ☹ [3]

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[3] Johannes K Fichte, Markus Hecher, Michael Morak, and Stefan Woltran. **Answer set solving with bounded treewidth revisited.** In LPNMR 2017.

Which Weighting Function? Absolute vs. Relative Weights

Natural choice?

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Relative Weights:
cheaper methods to quantify effects

- Count Supported Models with $\omega_{\#_{\mathcal{S}}}$

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

$$\omega_{\#_{\mathcal{S}}}(b,\Pi,\epsilon) = 1 \quad \downarrow$$

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

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Which Weighting Function? Absolute vs. Relative Weights

Natural choice?

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Counting answer sets is hard ☹ [fichte2017answer]

Relative Weights:
cheaper methods to quantify effects

- Count Supported Models with $\omega_{\#_{\mathcal{S}}}$
- Count Facets with $\omega_{\#_{\mathcal{F}}}$

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

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

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

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

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

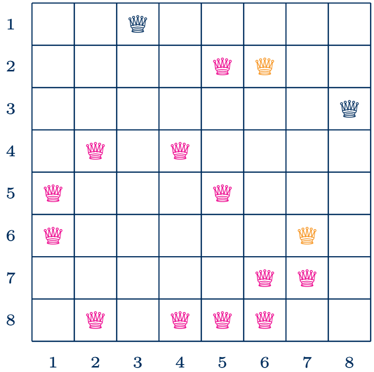
$$\mathcal{AS}(\Pi^{\langle \overline{c} \rangle}) = \{\{a,e\},\{b,d,e\}\}$$

[3] Johannes K Fichte, Markus Hecher, Michael Morak, and Stefan Woltran. **Answer set solving with bounded treewidth revisited.** In LPNMR 2017.

Quantitative Arguments

	2		5		1		9	
8			2		3			6
	3			6			7	
6	*6*	1		*2*	*2|6*			
5	4			*2*		*8*	1	9
				2|5	*2|5*	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 (1/4)/most (3/4) impact?

Part 2 Incremental Answer Set Counting

Counting Efficiently via Knowledge Compilation [4]

$\Pi_1 = \{a \leftarrow b., b \leftarrow ., c \leftarrow c\}$ transform to sd-DNNF $\Phi_{\Pi_1} = ((x_3 \wedge \neg c) \vee (\neg x_3 \wedge c)) \wedge (\neg x_1 \wedge \neg x_2 \wedge \neg x_5 \wedge a \wedge b)$

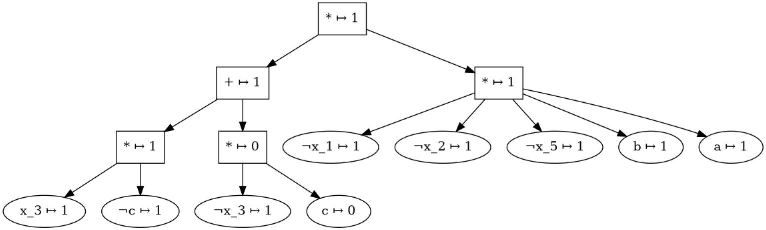


Figure 2: Counting graph $\mathcal{G}_{\Pi_1}^{\langle \sim c \rangle}$ labeled with evaluations.

[4] Johannes Klaus Fichte, SAG, Markus Hecher, Dominik Rusovac. **IASCAR: Incremental Answer Set Counting by Anytime Refinement**; LPNMR 2022, honorable mention.

Answer Sets versus Supported Models

Logic program Π:

$a \leftarrow b \qquad b \leftarrow a$

$c \leftarrow \neg d \qquad d \leftarrow \neg c$

$a \leftarrow c, e \qquad e \leftarrow c$

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

Supported models : $\mathcal{S}(\Pi) = \{\{a, b, c, e\}, \{d\}, \{a, b, d\}\}$

Answer Sets versus Supported Models

Completion:

$$a \leftrightarrow b \vee (c \wedge e) \qquad b \leftrightarrow a$$

$$c \leftrightarrow \neg d \qquad d \leftrightarrow \neg c$$

$$e \leftrightarrow c$$

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

Supported models: models of completion

Answer Sets versus Supported Models

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In general $\mathcal{AS}(\Pi) \subseteq \mathcal{S}(\Pi)$

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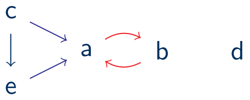
Positive dependency graph:



Mismatch caused by **cycle** $\{a, b\}$
with no **external support** $\{c, e\}$

Answer Sets versus Supported Models

Logic program Π:

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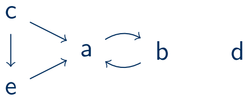
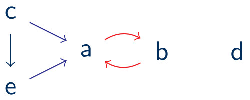


(No cycles $\Leftrightarrow$ Π is **tight**)
$\Rightarrow \mathcal{AS}(\Pi) = \mathcal{S}(\Pi)$ [**cois1994consistency**]

Identifying Cycles without External Support



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

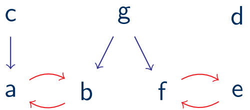
$\mathcal{S}(\Pi) = \{\{a, b, c, e\}, \{d\}, \underline{\{a, b, d\}}\}$

Unsupported constraint

- Rule of form $\leftarrow \underbrace{c_0, \ldots, c_n}_{\text{cycle}}, \underbrace{\neg s_0, \ldots, \neg s_m}_{\text{external support}}$
- Example: $r = \leftarrow a, b, \neg c, \neg e$

- **Pruning** mismatch: $\mathcal{S}(\Pi \cup \{r\}) = \mathcal{AS}(\Pi)$
- **Identifying** mismatch: $\mathcal{S}(\Pi^{B(r)}) = \mathcal{S}(\Pi) \setminus \mathcal{AS}(\Pi)$ where $B(r) = \{a, b, \neg c, \neg e\}$

Incremental Answer Set Counting with Anytime Refinement



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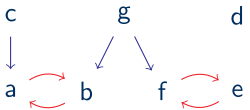

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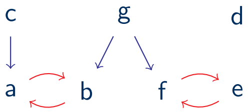
Counting by $a_d^L \coloneqq \sum_{i=0}^{d} (-1)^i \sum_{\Gamma \in \Lambda_i(\Pi)} |\mathcal{S}(\Pi^{L \cup B(\Gamma)})|$ with **alternation depth** d

Incremental Answer Set Counting with Anytime Refinement



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1. **Include** all supported models under assumptions L by $|\mathcal{S}(\Pi^L)|$

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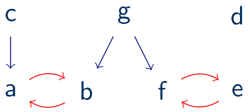

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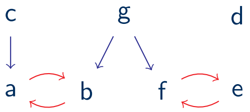
1. **Include** all supported models under assumptions L by $|\mathcal{S}(\Pi^{L})|$
2. **Exclude** mismatches identified via singleton cycles by $-\sum_{\Gamma \in \Lambda_1(\Pi)} |\mathcal{S}(\Pi^{L \cup B(\Gamma)})|$

Incremental Answer Set Counting with Anytime Refinement



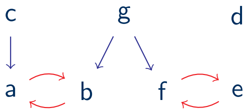
$\mathcal{S}(\Pi) = \{\{d\}, \{d, e, f\}, \{a, b, d\}, \{a, b, c\}, \{a, b, c, e, f\}, \{a, b, d, e, f\}\}$

Counting by $a_d^L \coloneqq \sum_{i=0}^{d} (-1)^i \sum_{\Gamma \in \Lambda_i(\Pi)} |\mathcal{S}(\Pi^{L \cup B(\Gamma)})|$ with **alternation depth** d

1. **Include** all supported models under assumptions L by $|\mathcal{S}(\Pi^L)|$
2. **Exclude** mismatches identified via singleton cycles by $-\sum_{\Gamma \in \Lambda_1(\Pi)} |\mathcal{S}(\Pi^{L \cup B(\Gamma)})|$
3. **Include** mistakenly excluded models by $+\sum_{\Gamma \in \Lambda_2(\Pi)} |\mathcal{S}(\Pi^{L \cup B(\Gamma)})|$ via combining 2 cycles

$\vdots$

Incremental Answer Set Counting with Anytime Refinement



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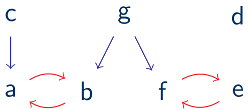
Example

$$a_1^{\{d\}} = |\mathcal{S}(\Pi^{\{d\}})| - |\mathcal{S}(\Pi^{\{d,a,b,\neg c,\neg g\}})| - |\mathcal{S}(\Pi^{\{d,e,f,\neg g\}})| = 0 \neq |\mathcal{AS}(\Pi^{\{d\}})| = 1$$

$$a_2^{\{d\}} = a_1^{\{d\}} + |\mathcal{S}(\Pi^{\{d,a,b,\neg c,\neg g,e,f\}})| = |\mathcal{AS}(\Pi^{\{d\}})| = 1$$

Incremental Answer Set Counting with Anytime Refinement



$$\mathcal{S}(\Pi) = \{\{d\}, \{d, e, f\}, \{a, b, d\}, \{a, b, c\}, \{a, b, c, e, f\}, \{a, b, d, e, f\}\}$$

Example

$$a_1^{\{d\}} = |\mathcal{S}(\Pi^{\{d\}})| - |\mathcal{S}(\Pi^{\{d,a,b,\neg c,\neg g\}})| - |\mathcal{S}(\Pi^{\{d,e,f,\neg g\}})| = 0 \neq |\mathcal{AS}(\Pi^{\{d\}})| = 1$$

$$a_2^{\{d\}} = a_1^{\{d\}} + |\mathcal{S}(\Pi^{\{d,a,b,\neg c,\neg g,e,f\}})| = |\mathcal{AS}(\Pi^{\{d\}})| = 1$$

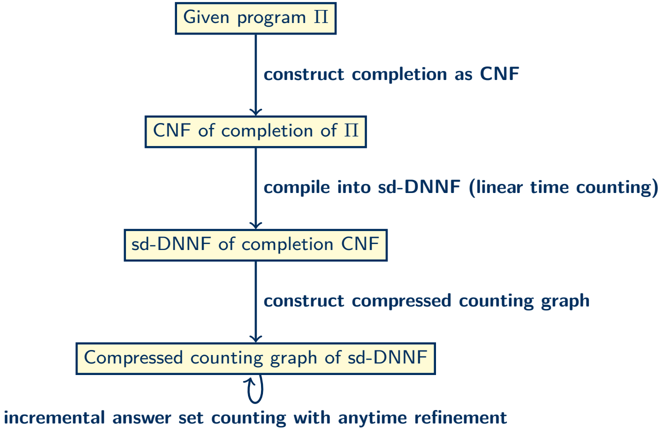
Theorem (Exact Counting)

If $d = |\mathrm{cycles}(\Pi)|$, *then* $a_d^L = |\mathcal{AS}(\Pi^L)|$.

Theorem (Early Termination)

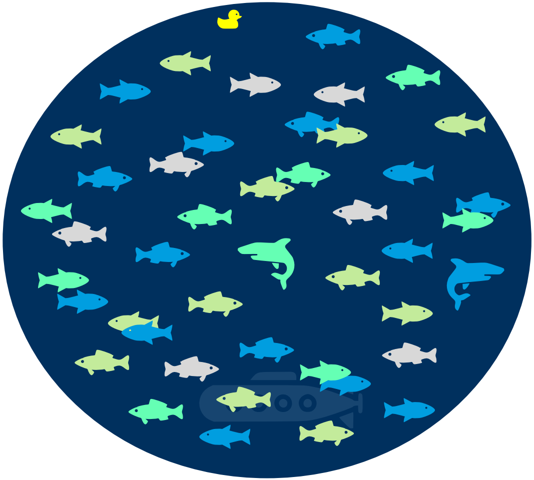
If $a_i^L = a_{i+1}^L$, *then* $a_i^L = |\mathcal{AS}(\Pi^L)|$.

Architecture IASCAR Tool



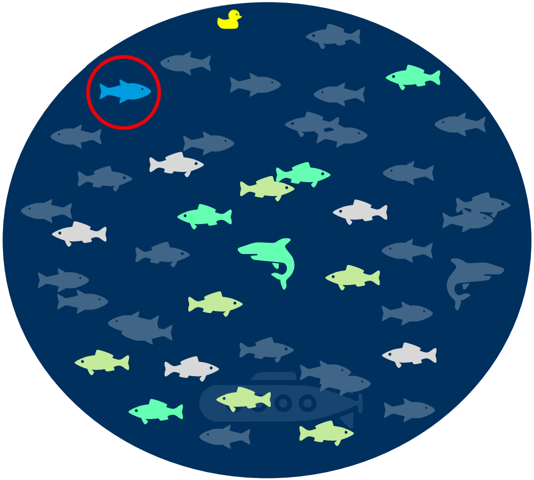
Part 3 Diverse Answer Sets

Reworking Methods [5]



[5] Elisa Böhl, SAG. **Tunas - Fishing for Diverse Answer Sets: A Multi-Shot Trade up Strategy**; LPNMR 2022.

Reworking Methods [5]



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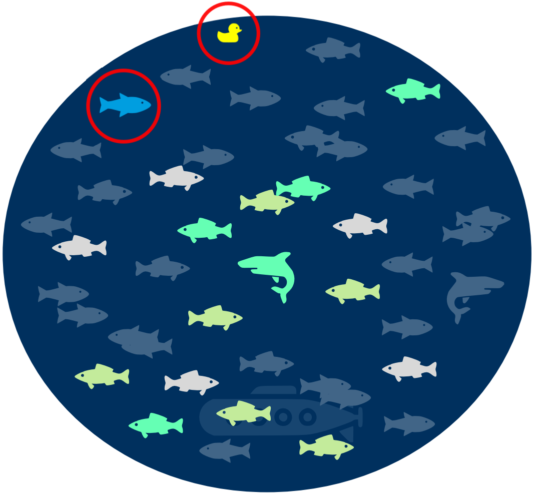
Reworking Methods [5]



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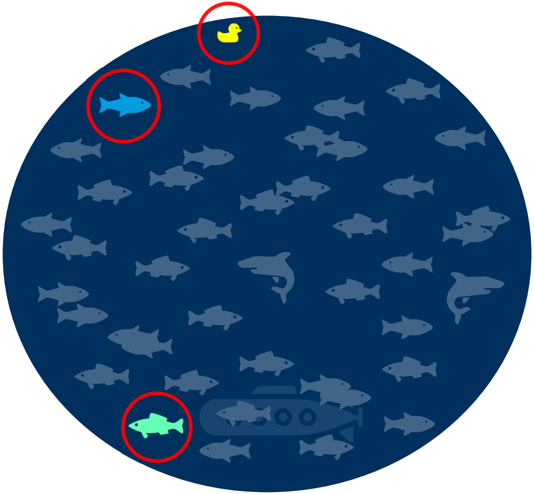
Reworking Methods [5]



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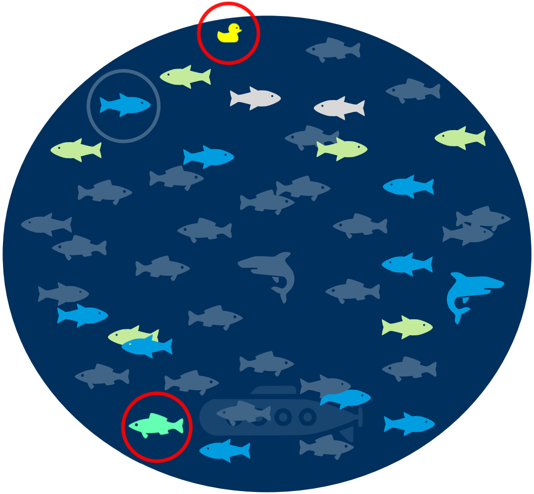
Reworking Methods [5]



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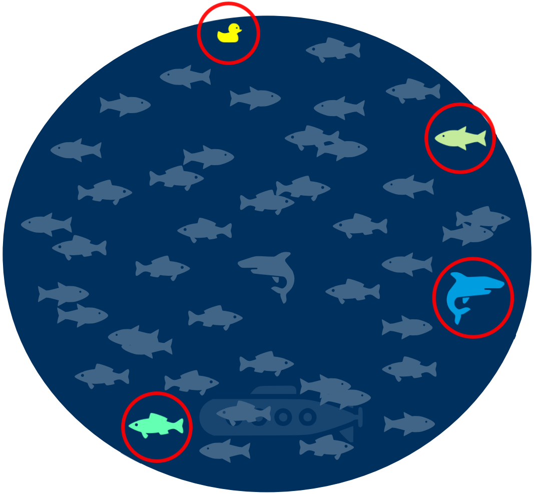
Reworking Methods [5]



[5] Elisa Böhl, SAG. **Tunas - Fishing for Diverse Answer Sets: A Multi-Shot Trade up Strategy**; LPNMR 2022.

Reworking Methods [5]

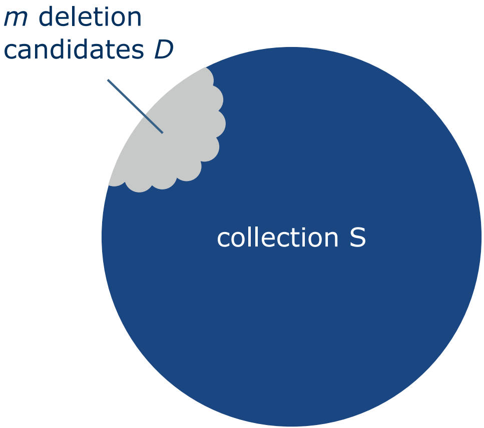
Problem Definition

[5] Elisa Böhl, SAG. **Tunas - Fishing for Diverse Answer Sets: A Multi-Shot Trade up Strategy**; LPNMR 2022.

Reworking Methods [5]

Problem Definition

– $|S \setminus S'| \leq m$

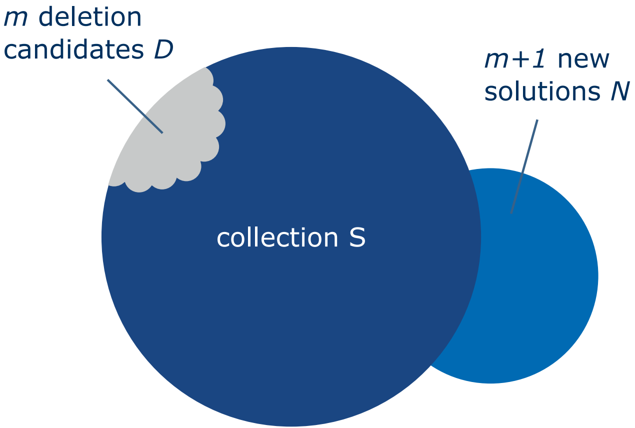


[5] Elisa Böhl, SAG. **Tunas - Fishing for Diverse Answer Sets: A Multi-Shot Trade up Strategy**; LPNMR 2022.

Reworking Methods [5]

Problem Definition

- $|S'| > |S|$
- $|S \setminus S'| \leq m$



[5] Elisa Böhl, SAG. **Tunas - Fishing for Diverse Answer Sets: A Multi-Shot Trade up Strategy**; LPNMR 2022.

Reworking Methods [5]

Problem Definition

- $|S'| > |S|$
- $|S \setminus S'| \leq m$
- $\Delta(S') \geq k$

[5] Elisa Böhl, SAG. **Tunas - Fishing for Diverse Answer Sets: A Multi-Shot Trade up Strategy**; LPNMR 2022.

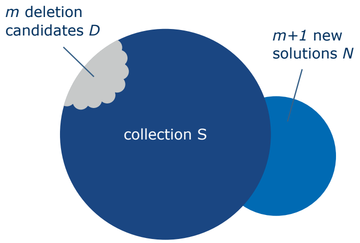
Reworking Methods [5]

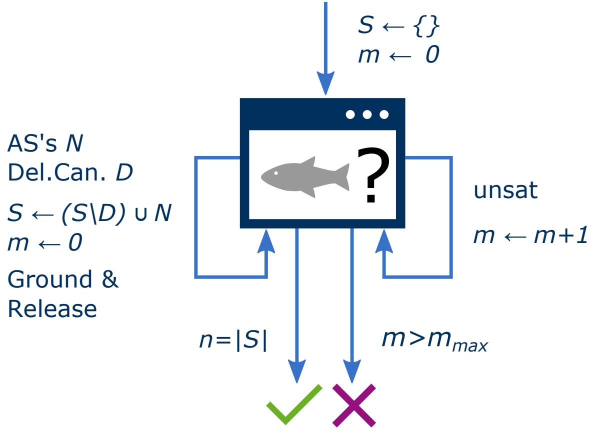
Problem Definition

- $|S'| > |S|$
- $|S \setminus S'| \leq m$
- $\Delta(S') \geq k$
- NP-complete

[5] Elisa Böhl, SAG. **Tunas - Fishing for Diverse Answer Sets: A Multi-Shot Trade up Strategy**; LPNMR 2022.

Tunas - Trade Up Navigation for Answer Sets

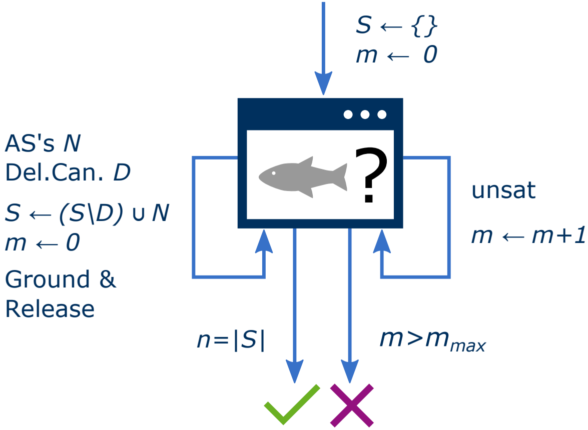




Tunas - Trade Up Navigation for Answer Sets

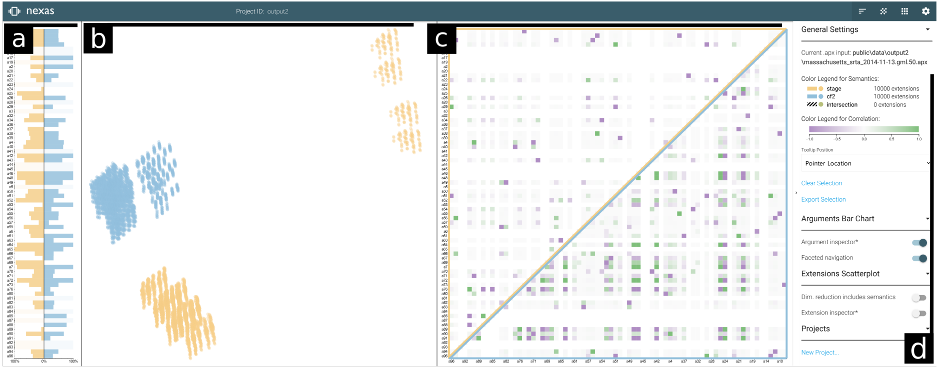
Properties

- comparatively fast
- anytime approach
- multi-shot
  - additive grounding
  - concealment and deletion of atoms
  - counting over changing domain



Part 4 Visual Approach for Solution Space Exploaration

NEXAS: A Visual Tool for Navigating and Exploring Argumentation Solution Spaces [6]



[6] Raimund Dachselt, SAG, Markus Krötzsch, Julián Méndez, Dominik Rusovac, Mei Yang. **NEXAS: A Visual Tool for Navigating and Exploring Argumentation Solution Spaces**; COMMA 2022. `https://imld.de/nexas`

Summary & Future Work

Summary:

- Weighted faceted navigation allows to quantitatively explore the solution space
- Incremental answer set counting via knowledge compilation and anytime refinement
- Iterative reworking strategies to comupte diverse answer sets
- Visual exploration of solution space

Future Work:

- Further interesting properties of facet-counting weight
- Measure the quality of diverse solutions
- Generalize visualization approach for answer sets