## Quantitative and Stream Extensions of ASP

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Answer Set Programming Extensions

# Answer Set Programming

Answer Set Programming (ASP):

- Non-monotonic
- Default Negation

$$a \leftarrow b_1, \ldots, b_n, \text{not } b_{n+1}, \ldots, \text{not } b_m$$

Solve NP-hard Problems

Introduction Problem Answer Set Programming Our Work Extensions Summary





#### $fail \gets overheat$

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ASP

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#### (TD) Temporal Domain (e.g. LARS [Beck et al., 2018]):

 $\text{fail} \gets \boxplus^5 \square \text{overheat}$ 

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(QM) Quantitative Reasoning over Models (e.g. *asprin* [Brewka *et al.*, 2015]):

#optimize(temp)

(QC) Quantitative Constraints (e.g. Weight Constraints [Niemela *et al.*, 1999]):

fail  $\leftarrow \text{temp}(X), X > 100$ 

Problem Statement State of the Art Methodology

# **Problem Statement**

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Find and analyze a general framework that combines

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# Challenges

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Time domain and specification of quantities not orthogonal

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- Differentiate aggregates at a given timepoint and aggregates over all timepoints

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#### Challenge II: Entangle Time & Quantitative Reasoning

- Time domain and specification of quantities not orthogonal
- Differentiate aggregates at a given timepoint and aggregates over all timepoints
- Statements of the form w : φ insufficient!

## State of the Art

Quantitative Constraints:

- Hybrid ASP [Cabalar et al., 2020]
- Nested Expressions [Ferraris, 2011]

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- ▶ LP<sup>MLN</sup> [Lee and Yang, 2017]
- Algebraic Prolog [Kimmig *et al.*, 2011; Belle and De Raedt, 2016]

## State of the Art

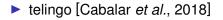
Quantitative Constraints:

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Combination:



# Approach: Semirings

 Semirings can be used to parameterise calculations [Green et al., 2007][Bistarelli et al., 2018]

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- Semirings can be used to parameterise calculations [Green et al., 2007][Bistarelli et al., 2018]
- ▶ A semiring is an algebraic structure  $(R, \oplus, \otimes, e_{\oplus}, e_{\otimes})$ , s.t.
  - ▶  $(R, \oplus, e_{\oplus})$  is a commutative monoid with neutral element  $e_{\oplus}$
  - $(R, \otimes, e_{\otimes})$  is a monoid with neutral element  $e_{\otimes}$
  - multiplication ( $\otimes$ ) distributes over addition ( $\oplus$ )
  - ▶ multiplication by  $e_{\oplus}$  annihilates R( $\forall r \in R : e_{\oplus} \otimes r = e_{\oplus} = r \otimes e_{\oplus}$ )

# Semiring Examples

Prominent examples are

Problem Statemen State of the Art Methodology

# Weighted Logic [Droste and Gastin, 2007]

 $\alpha ::= \mathbf{k} \mid \mathbf{p} \mid \neg \mathbf{p} \mid \alpha \land \alpha \mid \alpha \lor \alpha \mid \dots$ 

k semiring value, p atomic formula

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# Weighted Logic [Droste and Gastin, 2007]

$$\alpha ::= \mathbf{k} \mid \mathbf{p} \mid \neg \mathbf{p} \mid \alpha * \alpha \mid \alpha + \alpha \mid \dots$$

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Problem Statemen State of the Art Methodology

Weighted Logic [Droste and Gastin, 2007]

$$\alpha ::= \mathbf{k} \mid \mathbf{p} \mid \neg \mathbf{p} \mid \alpha * \alpha \mid \alpha + \alpha \mid \dots$$

k semiring value, p atomic formula

"Disjunction is addition and conjunction is multiplication"

$$\llbracket k \rrbracket_{\mathcal{R}}(\mathcal{I}) = k$$
$$\llbracket p \rrbracket_{\mathcal{R}}(\mathcal{I}) = \begin{cases} e_{\otimes}, & \text{if } p \in \mathcal{I} \\ e_{\oplus}, & \text{otherwise.} \end{cases}$$
$$\llbracket \alpha * \beta \rrbracket_{\mathcal{R}}(\mathcal{I}) = \llbracket \alpha \rrbracket_{\mathcal{R}}(\mathcal{I}) \otimes \llbracket \beta \rrbracket_{\mathcal{R}}(\mathcal{I}) \\ \llbracket \alpha + \beta \rrbracket_{\mathcal{R}}(\mathcal{I}) = \llbracket \alpha \rrbracket_{\mathcal{R}}(\mathcal{I}) \oplus \llbracket \beta \rrbracket_{\mathcal{R}}(\mathcal{I}) \end{cases}$$

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| Problem     | State of the Art |
| Our Work    | Methodology      |
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## Example

$$\alpha = 15 * \text{Circus} + 20 * \text{Restaurant}$$
  
 $\mathcal{I} = \{\text{Circus}\}$ 

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#### Example

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Over the semiring  $\mathbb{Q}$ :

$$\llbracket lpha 
rbracket_{\mathbb{Q}}(\mathcal{I}) = \mathsf{15} \cdot \mathsf{1} + \mathsf{20} \cdot \mathsf{0} = \mathsf{15}.$$

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#### Example

$$\alpha = 15 * \text{Circus} + 20 * \text{Restaurant}$$
  
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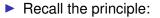
Over the semiring  $\mathbb{Q}$ :

$$\llbracket \alpha \rrbracket_{\mathbb{Q}}(\mathcal{I}) = 15 \cdot 1 + 20 \cdot 0 = 15.$$

Over the min tropical semiring  $\mathcal{R}_{min} = (\mathbb{R} \cup \{\infty\}, \min, +, \infty, 0)$ :

$$\llbracket \alpha \rrbracket_{\mathcal{R}_{\min}}(\mathcal{I}) = \min(15 + 0, 20 + \infty) = 15.$$

# Appeal of Weighted Logic



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Recall the principle:

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Semantics often defined via disjunction and conjunction

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- Semantics often defined via disjunction and conjunction
- E.g. existential quantification over timepoints is sum over timepoints
  - $\hookrightarrow$  Weighted Logic as a generic tool

# Appeal of Weighted Logic

Recall the principle:

"Disjunction is addition and conjunction is multiplication"

- Semantics often defined via disjunction and conjunction
- E.g. existential quantification over timepoints is sum over timepoints
  - $\hookrightarrow$  Weighted Logic as a generic tool
- ► E.g. Here-and-There Logic → non-monotonicity → Weighted Here-and-There Logic → non-monotonic calculation



Thomas Eiter and Rafael K\_, Weighted LARS for Quantitative Stream Reasoning, European Conference on Artificial Intelligence, 2020



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- LARS is a stream reasoning framework with answer set semantics
- Introduced a weighted version of LARS
  - $\hookrightarrow$  Addresses challenge II



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- LARS is a stream reasoning framework with answer set semantics
- Introduced a weighted version of LARS
  - $\hookrightarrow \mathsf{Addresses} \ \mathsf{challenge} \ \mathsf{II}$
- Showed its power as an underlying framework for
  - Probabilities
  - Preferences
  - Weighted Model Counting
  - $\hookrightarrow \mathsf{Addresses} \ \mathsf{challenge} \ \mathsf{I}$



Thomas Eiter and Rafael K\_, ASPAC: Answer Set Programming with Algebraic Constraints, International Conference on Logic Programming, 2020



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- Introduced First-Order Weighted Here-and-There Logic
   Calculations over semirings with non-monotonic dependency



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- Introduced First-Order Weighted Here-and-There Logic
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- Algebraic Constraints subsume
  - Aggregates
  - Choice Constraints
  - Weight Constraints with Conditionals
  - ▶ ...
  - $\hookrightarrow \mathsf{Addresses} \ \mathsf{challenge} \ \mathsf{I}$



- Thomas Eiter and Rafael K\_, ASPAC: Answer Set Programming with Algebraic Constraints, International Conference on Logic Programming, 2020
- Introduced First-Order Weighted Here-and-There Logic
   Calculations over semirings with non-monotonic dependency
- Algebraic Constraints subsume (with mild practical restrictions)
  - Aggregates
  - Choice Constraints
  - Weight Constraints with Conditionals
  - ▶ ...
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## Semiring Complexity

Thomas Eiter and Rafael K\_, On the Complexity of Sum-Of-Products Problems over Semirings, AAAI Conference on Artificial Intelligence, 2021 Introduction Problem Progress Our Work Current Resear Summary

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- Thomas Eiter and Rafael K\_, On the Complexity of Sum-Of-Products Problems over Semirings, AAAI Conference on Artificial Intelligence, 2021
- In depth analysis of the complexity of weighted model counting over semirings

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# Semiring Complexity

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- In depth analysis of the complexity of weighted model counting over semirings
- Can be very hard (up to undecidable)
- We identified classes that can be solved with #SAT or SAT-solvers



Thomas Eiter, Markus Hecher and Rafael K\_, Treewidth-Aware Cycle-Breaking for Algebraic Answer Set Counting, International Conference on Principles of Knowledge Representation and Reasoning, 2021 (to Appear)



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- Prototypical implementation: aspmc



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- Novel treewidth-aware translation from ASP to CNF
- Prototypical implementation: aspmc
- aspmc partially outperforms other solvers on standard benchmarks

Introduction Problem Progress Our Work Current Research Summary

#### What is next?

Practical evaluation on real world example





- Practical evaluation on real world example
- Additional improvements of the efficiency of aspmc



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- Practical evaluation on real world example
- Additional improvements of the efficiency of aspmc
- Further analysis and comparisons in journal versions





 Weighted Logic is to quantities what Here-And-There Logic is to non-monotonicity





- Weighted Logic is to quantities what Here-And-There Logic is to non-monotonicity
- Unify quantitative extensions





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- Easily adjustable to the given domain





- Weighted Logic is to quantities what Here-And-There Logic is to non-monotonicity
- Unify quantitative extensions
- Easily adjustable to the given domain
- ► General formalism is found and partially implemented → further analysis and real world application



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