Magic-Sets for Datalog with Existential Quantifiers

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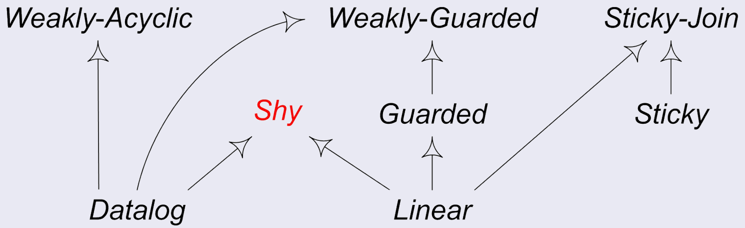
Introduction (1)

- Datalog$^\exists$
  - Datalog + unrestricted existential quantification
  - Highly expressive
  - Undecidable reasoning

Several decidable fragments



Introduction (2)

- Datalog programs are usually evaluated bottom-up
  - Queries may be handled inefficiently
- Query optimization in Datalog $\Longrightarrow$ Magic-Sets
  - Identify relevant atoms for the query

Main contributions

Magic-Sets for Datalog$^{\exists}$ programs

- Query-equivalent to the original program in general
- Closed on Shy
- Implementation in DLV
- Comparison with ontology reasoners

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Outline

1. Datalog$^\exists$
   - Syntax, semantics and queries
   - CHASE procedure and top-down evaluation
2. Magic-Sets
   - Example
   - Application to Shy and experiment

Datalog$^\exists$ programs and queries

Rule structure

$$\forall \mathbf{X} \exists \mathbf{Y} \; atom_{[\mathbf{X}' \cup \mathbf{Y}]} \leftarrow conj_{[\mathbf{X}]}$$

Query structure

$$\exists \mathbf{Y} \; conj_{[\mathbf{X}]}?$$

Example. Datalog$^\exists$ program

r_1 : $\exists \mathtt{Y}\ \mathtt{father}(\mathtt{Y},\mathtt{X}) \leftarrow \mathtt{father}(\mathtt{X},\mathtt{Z})$

r_2 : $\mathtt{grandFather}(\mathtt{X},\mathtt{Y}) \leftarrow \mathtt{father}(\mathtt{X},\mathtt{Z}),\ \mathtt{father}(\mathtt{Z},\mathtt{Y})$

Database

$\mathtt{father}(\mathtt{a},\mathtt{b}) \leftarrow$
$\mathtt{father}(\mathtt{b},\mathtt{c}) \leftarrow$

Example. Queries

Q_1 : $\mathtt{grandFather}(\mathtt{a},\mathtt{Y})?$

Q_2 : $\exists \mathtt{Y}\ \mathtt{grandFather}(\mathtt{Y},\mathtt{a})?$

Datalog$^\exists$ semantics

Let M be a set of ground atoms, and P be a program with rules

$$r: \ \forall \mathbf{X} \exists \mathbf{Y}\ atom_{[\mathbf{X}' \cup \mathbf{Y}]} \leftarrow conj_{[\mathbf{X}]}$$

Atom entailment

$M \models a$ if there is a substitution σ s.t. $\sigma(a) \in M$.

Rule satisfaction

$M \models r$ if $M \models \sigma|_{\mathbf{X}}(atom)$ whenever $\sigma(conj) \subseteq M$.

Definition (Model)

$M \models P$ if $M \models r$, for all $r \in P$.

Warning!

Unrestricted universe

How many models?
How many subset-minimal models?

$r_1: \ \exists \mathtt{Y}\ \mathtt{father(Y,X)} \leftarrow \mathtt{father(X,Z)}$

$\mathtt{father(a,b)} \leftarrow$

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Query answering

Let P be a program, and Q be a query

$$\exists \mathbf{Y}\ conj_{[\mathbf{X}]}$$

Query answers

$$ans_P(Q) = \{\sigma|_{\mathbf{X}} \mid M \models \sigma|_{\mathbf{X}}(conj) \text{ for all models } M \text{ of } P\}$$

Infinitely many models

Cannot count them in finite time!

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Universal model

U is a universal model of *P* if

- $U \models P$ and
- for each model *M* of *P* there is a mapping *h* s.t. $h(U) \subseteq M$.

Theorem (Fagin et al. 2005)

$ans_P(Q) = \{\sigma|_{\mathbf{X}} \mid \sigma(\mathbf{X})$ *is a set of constants and* $U \models \sigma|_{\mathbf{X}}(conj)\}$

CHASE procedure

Constructs a universal model

CHASE procedure at work

D : fat(a, b) ←; fat(b, c) ←

r_1 : ∃Y fat(Y, X) ← fat(X, Z)

r_2 : grFat(X, Y) ← fat(X, Z), fat(Z, Y)

Stop it?

Undecidable in general!

∃Y grFat(Y, a)?

Yes!

Not query-driven!

Also computes irrelevant atoms

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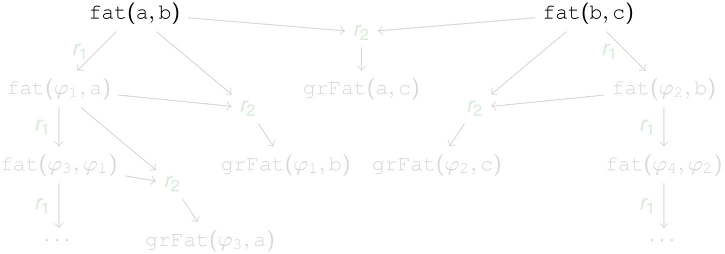

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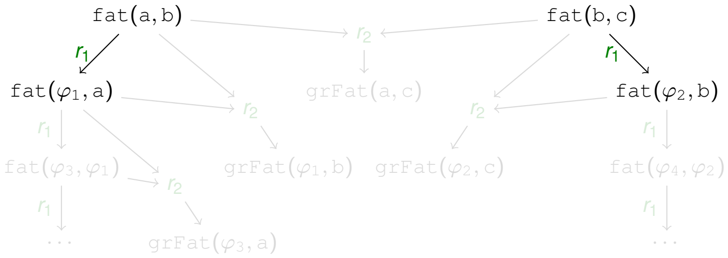

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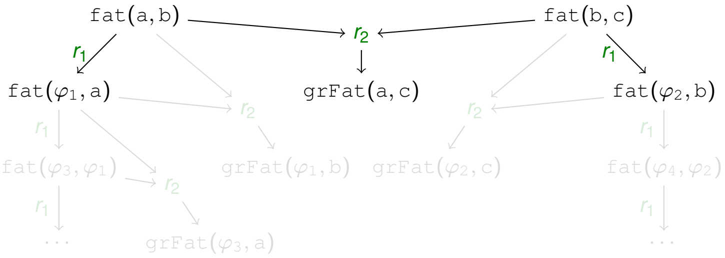

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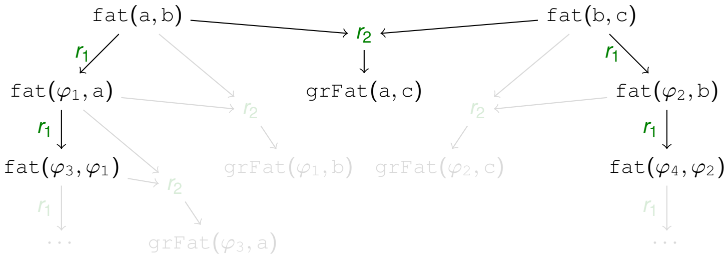

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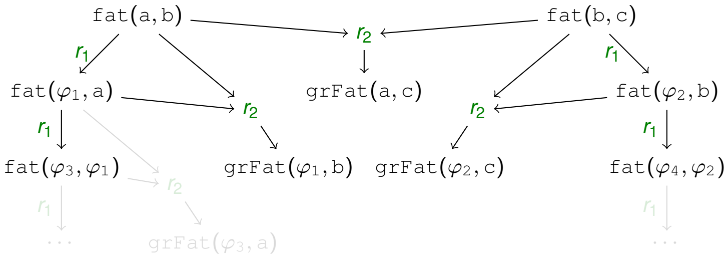

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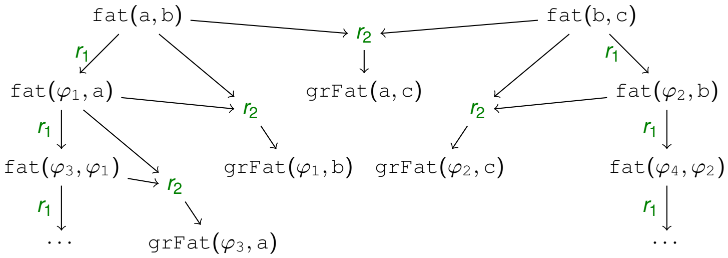

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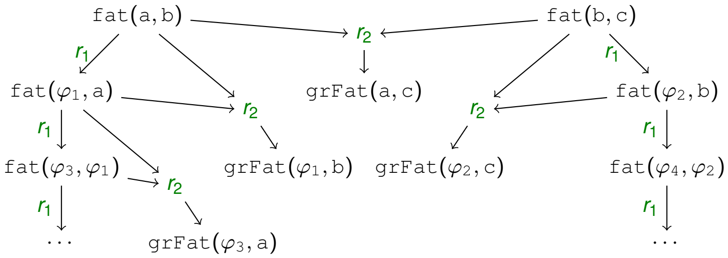

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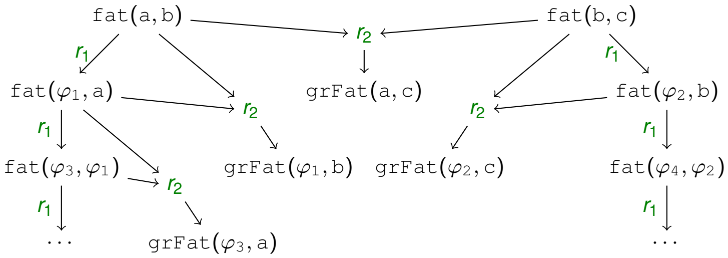

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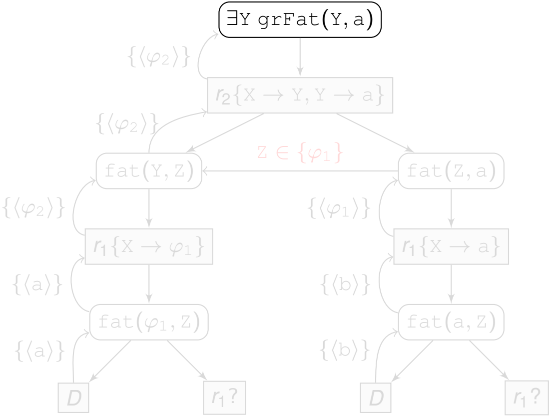
Top-down evaluation of $\exists Y\ grFat(Y, a)$



The query is true!

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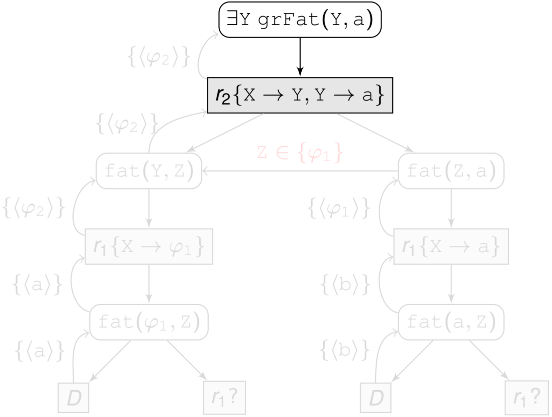

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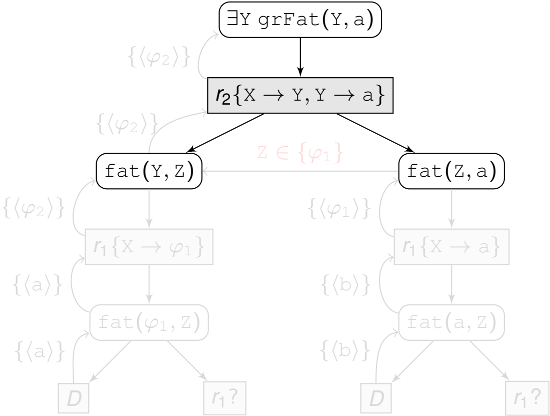

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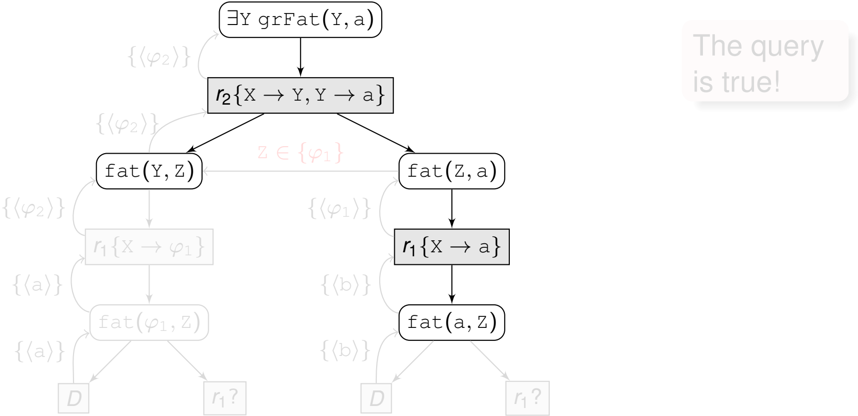

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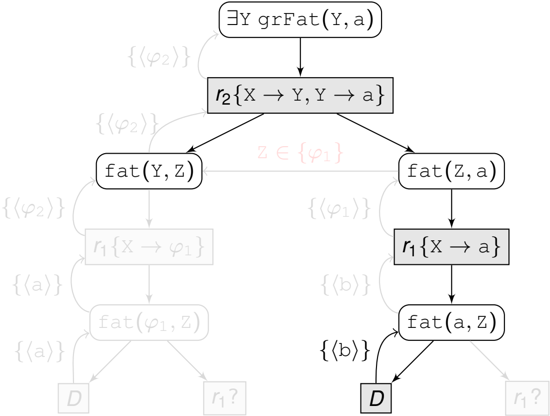

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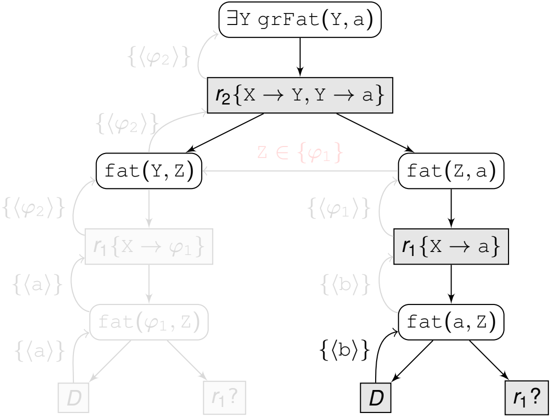

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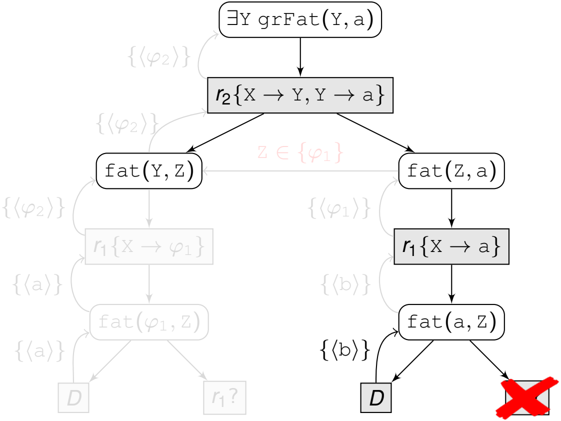

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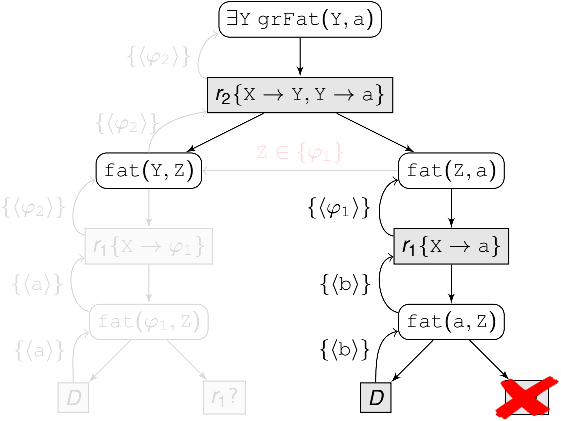

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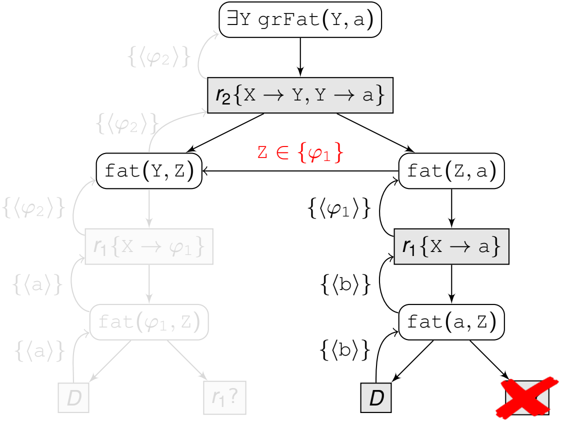

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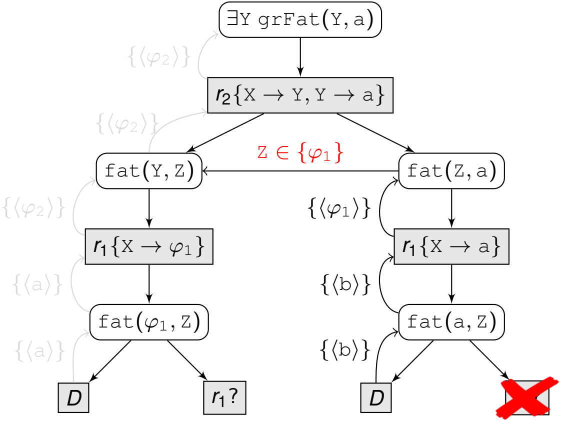

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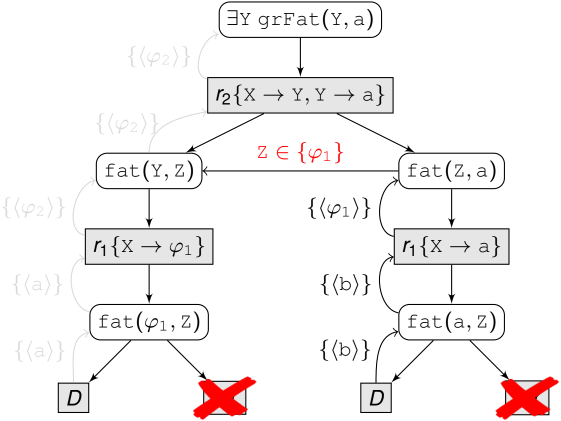

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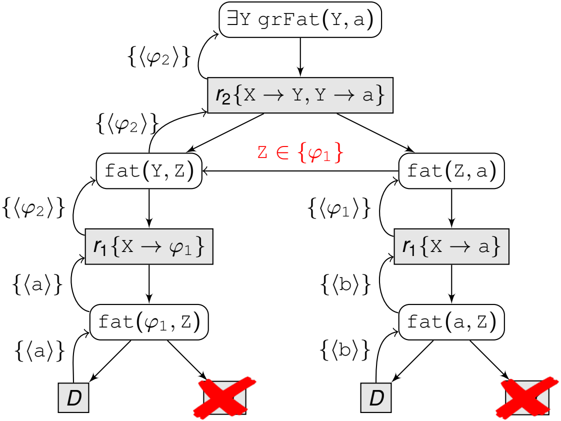

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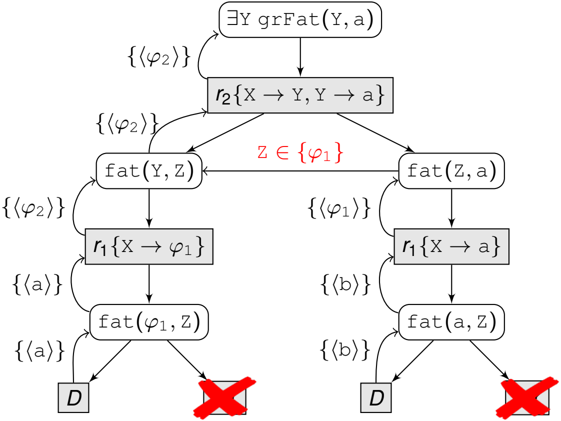

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Magic-Sets: Example

- Aim at combining the benefit of the two approaches
- Only infer relevant atoms during the CHASE procedure

Q : $\exists \mathtt{Y}\ \mathtt{grFat}(\mathtt{Y}, \mathtt{a})?$

r_1 : $\exists \mathtt{Y}\ \mathtt{fat}(\mathtt{Y}, \mathtt{X}) \leftarrow \mathtt{fat}(\mathtt{X}, \mathtt{Z})$

r_2 : $\mathtt{grFat}(\mathtt{X}, \mathtt{Y}) \leftarrow \mathtt{fat}(\mathtt{X}, \mathtt{Z}),\ \mathtt{fat}(\mathtt{Z}, \mathtt{Y})$

r^*_Q : $\mathtt{mgc\_grFat}^{\mathtt{fb}}(\mathtt{a}) \leftarrow$

r^*_1 : $\mathtt{mgc\_fat}^{\mathtt{bf}}(\mathtt{X}) \leftarrow \mathtt{mgc\_fat}^{\mathtt{fb}}(\mathtt{X})$

$r^*_{2,1}$: $\mathtt{mgc\_fat}^{\mathtt{fb}}(\mathtt{Y}) \leftarrow \mathtt{mgc\_grFat}^{\mathtt{fb}}(\mathtt{Y})$

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Magic-Sets: Example

- Aim at combining the benefit of the two approaches
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$\Rightarrow$ Q : $\exists \mathtt{Y}\ \mathtt{grFat}(\mathtt{Y}, \mathtt{a})$?

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Process the query:

Magic-Sets: Example

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Process the query: produce r_Q^*

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$\Rightarrow$ r_2 : $\mathtt{grFat}(\mathtt{X}, \mathtt{Y}) \leftarrow \mathtt{fat}(\mathtt{X}, \mathtt{Z}),\ \mathtt{fat}(\mathtt{Z}, \mathtt{Y})$

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Process $\mathtt{mgc\_grFat}^{\mathtt{fb}}$ and r_2:

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Q : $\exists \mathtt{Y}\ \mathtt{grFat}(\mathtt{Y}, \mathtt{a})?$

r_1 : $\exists \mathtt{Y}\ \mathtt{fat}(\mathtt{Y}, \mathtt{X}) \leftarrow \mathtt{fat}(\mathtt{X}, \mathtt{Z})$

$\Rightarrow r_2$: $\mathtt{grFat}(\mathtt{X}, \mathtt{Y}) \leftarrow \mathtt{mgc\_grFat}^{\mathtt{fb}}(\mathtt{Y}),\ \mathtt{fat}(\mathtt{X}, \mathtt{Z}),\ \mathtt{fat}(\mathtt{Z}, \mathtt{Y})$

r_Q^* : $\mathtt{mgc\_grFat}^{\mathtt{fb}}(\mathtt{a}) \leftarrow$

r_1^* : $\mathtt{mgc\_fat}^{\mathtt{bf}}(\mathtt{X}) \leftarrow \mathtt{mgc\_fat}^{\mathtt{fb}}(\mathtt{X})$

$r_{2,1}^*$: $\mathtt{mgc\_fat}^{\mathtt{fb}}(\mathtt{Y}) \leftarrow \mathtt{mgc\_grFat}^{\mathtt{fb}}(\mathtt{Y})$

$r_{2,2}^*$: $\mathtt{mgc\_fat}^{\mathtt{fb}}(\mathtt{Z}) \leftarrow \mathtt{mgc\_grFat}^{\mathtt{fb}}(\mathtt{Y}),\ \mathtt{fat}(\mathtt{Z}, \mathtt{Y})$

Process $\mathtt{mgc\_grFat}^{\mathtt{fb}}$ and r_2: produce $r_{2,1}^*$, $r_{2,2}^*$ and modify r_2

Magic-Sets: Example

- Aim at combining the benefit of the two approaches
- Only infer relevant atoms during the CHASE procedure

Q : $\exists \mathtt{Y}\ \mathtt{grFat}(\mathtt{Y},\mathtt{a})?$

$\Rightarrow$ r_1 : $\exists \mathtt{Y}\ \mathtt{fat}(\mathtt{Y},\mathtt{X}) \leftarrow \mathtt{fat}(\mathtt{X},\mathtt{Z})$

r_2 : $\mathtt{grFat}(\mathtt{X},\mathtt{Y}) \leftarrow \mathtt{mgc\_grFat}^{\mathtt{fb}}(\mathtt{Y}),\ \mathtt{fat}(\mathtt{X},\mathtt{Z}),\ \mathtt{fat}(\mathtt{Z},\mathtt{Y})$

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Process $\mathtt{mgc\_fat}^{\mathtt{fb}}$ and r_1:

Magic-Sets: Example

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- Only infer relevant atoms during the CHASE procedure

Q : $\exists Y\ \mathtt{grFat}(Y, a)$?

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r_2 : $\mathtt{grFat}(X, Y) \leftarrow \mathtt{mgc\_grFat}^{fb}(Y),\ \mathtt{fat}(X, Z),\ \mathtt{fat}(Z, Y)$

r_Q^* : $\mathtt{mgc\_grFat}^{fb}(a) \leftarrow$

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Process $\mathtt{mgc\_fat}^{fb}$ and r_1: produce r_1^* and modify r_1

Magic-Sets: Example

- Aim at combining the benefit of the two approaches
- Only infer relevant atoms during the CHASE procedure

Q : $\exists Y\ \mathtt{grFat}(Y, a)$?
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Process $\mathtt{mgc\_fat}^{bf}$ and r_1?

Magic-Sets: Example

- Aim at combining the benefit of the two approaches
- Only infer relevant atoms during the CHASE procedure

Q : $\exists$Y grFat(Y, a)?

⇒ r_1 : $\exists$Y fat(Y, X) ← mgc_fat^{fb}(X), fat(X, Z)

r_2 : grFat(X, Y) ← mgc_grFat^{fb}(Y), fat(X, Z), fat(Z, Y)

r_Q^* : mgc_grFat^{fb}(a) ←

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$r_{2,1}^*$: mgc_fat^{fb}(Y) ← mgc_grFat^{fb}(Y)

$r_{2,2}^*$: mgc_fat^{fb}(Z) ← mgc_grFat^{fb}(Y), fat(Z, Y)

Process mgc_fat^{bf} and r_1? Do not pass binding to $\exists$-variables!

Magic-Sets: Impact on the CHASE procedure

Q : $\exists$Y grFat(Y, a)?

fat(a, b) $\leftarrow$; fat(b, c) $\leftarrow$

r_1 : $\exists$Y fat(Y, X) $\leftarrow$ fat(X, Z)

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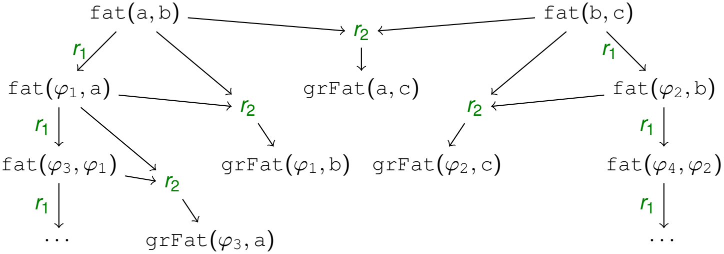

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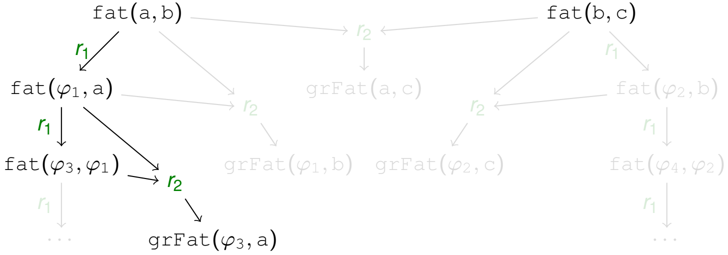

Outline

1. Datalog$^\exists$
   - Syntax, semantics and queries
   - CHASE procedure and top-down evaluation
2. Magic-Sets
   - Example
   - Application to Shy and experiment

Preserving shyness (1)

Informal definition

A program is Shy if nulls do not join in the CHASE.

Q : $\mathtt{q(a)?}$
D : $\mathtt{t(a)} \leftarrow$
r_1 : $\mathtt{q(X)} \leftarrow \mathtt{p(X,Y)},\ \mathtt{s(Y)},\ \mathtt{t(Y)}$
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Preserving shyness (2)

Observation

Shyness guarantees absence of joins on nulls

Q : $\mathtt{q(a)?}$
D : $\mathtt{t(a)} \leftarrow$
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Proposition

If the original program is shy, the modified program is shy as well and has the same models of the original program.

Theorem

Magic-Sets preserve shyness on the modified program.

Preserving shyness (2)

Observation

Shyness guarantees absence of joins on nulls

Q : q(a)?

D : t(a) ← ; #dom(a) ←

r_1 : q(X) ← p(X, Y), #dom(Y), s(Y), t(Y)

r_2 : ∃Y p(X, Y) ←

r_3 : s(Y) ← p(X, Y)

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Preserving shyness (3)

Q : $\mathtt{q(a)?}$

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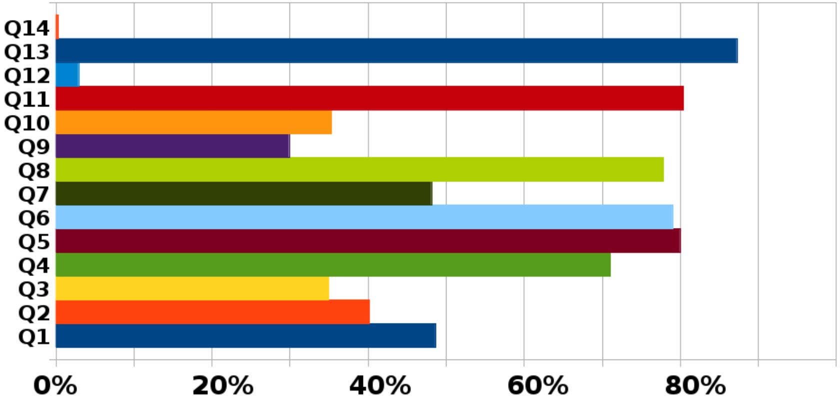
Experiment (1)

Dataset	System	# solved	Geom. Avg time
LUBM x10	DLV	14	2.87
	Pellet	14	84.48
	OWLIM-Lite	12	53.31
	OWLIM-SE	14	105.14
LUBM x30	DLV	14	9.70
	Pellet	0	–
	OWLIM-Lite	11	123.18
	OWLIM-SE	14	323.57
LUBM x50	DLV	14	16.67
	Pellet	0	–
	OWLIM-Lite	11	223.79
	OWLIM-SE	14	537.35

Experiment (2)

Improvement on LUMBx50



Conclusion

▸ Outline

- Novelty: handling of existential quantifiers
- Sound and complete for Datalog$^{\exists}$ programs in general
- Preserving shyness is possible
- Implementation in DLV
  - Sensible performance improvements
  - Outperforms state-of-the-art ontology-based systems

Future work

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- Application to other decidable classes
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Thank you!

Questions?