Query Evaluation Revised: Parallel, Distributed, via Rewritings

Doctoral Defence

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Query Evaluation

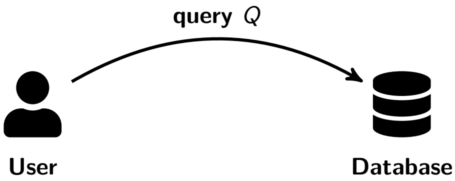
Classical Query Evaluation (simplified)

User

Database

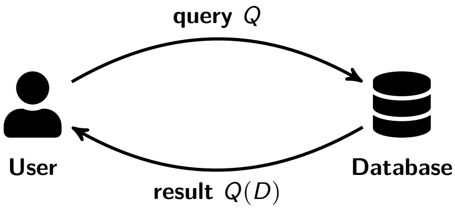
Query Evaluation

Classical Query Evaluation (simplified)



Query Evaluation

Classical Query Evaluation (simplified)



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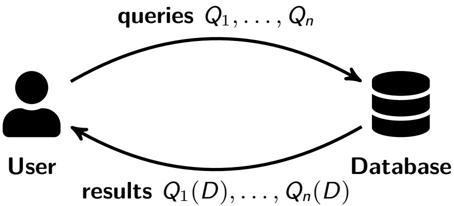
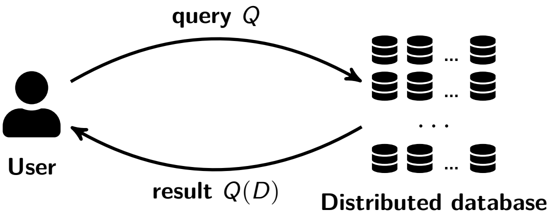

queries $Q_1, \ldots, Q_n$
User
Database
results $Q_1(D), \ldots, Q_n(D)$

Examples for Circumstances

- Multiple input queries

Query Evaluation

Query Evaluation (simplified)

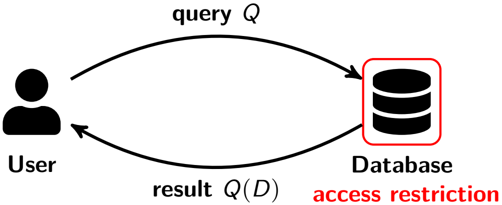


Examples for Circumstances

- Multiple input queries
- Distributed database(s)

Query Evaluation

Query Evaluation (simplified)

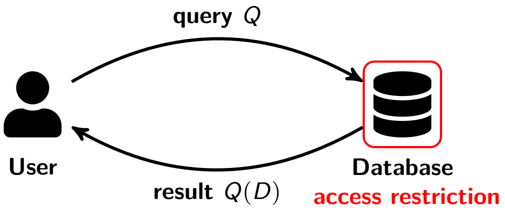


Examples for Circumstances

- Multiple input queries
- Distributed database(s)
- Access Restrictions

Query Evaluation

Query Evaluation (simplified)



Examples for Circumstances

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- ...

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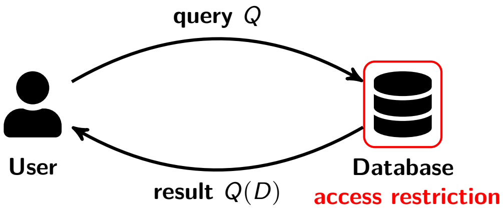

Examples for Circumstances

- Multiple input queries
- Distributed database(s)
- Access Restrictions
- ...

Questions

- Are methods from the classical setting still suitable?
  - Algorithms, Correctness, Complexity, ...

Query Evaluation

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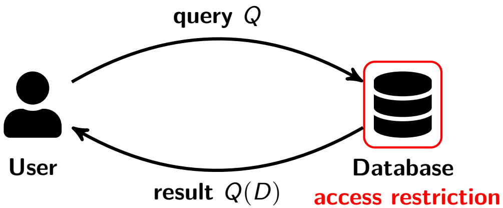

Examples for Circumstances

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- What is considered “suitable”?

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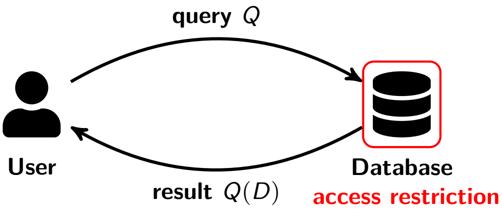

Examples for Circumstances

- Multiple input queries
- Distributed database(s)
- Access Restrictions
- ...

Questions

- Are methods from the classical setting still suitable?
  - Algorithms, Correctness, Complexity, ...
- What is considered “suitable”?
- (How) can methods be adapted?

Settings

1. Work-Efficient Constant-Time Parallel Query Evaluation

---

2. Parallel-Correctness and -Boundedness of Datalog Queries

---

3. Structurally Simple Rewritings

Settings

1. Work-Efficient Constant-Time Parallel Query Evaluation

data complexity

2. Parallel-Correctness and -Boundedness of Datalog Queries

static analysis

3. Structurally Simple Rewritings

static analysis

Settings

1. Work-Efficient Constant-Time Parallel Query Evaluation
   Preliminary results published at ICDT'23, Ioannina, Greece
   (Keppeler, Schwentick, and **S.** 2023)

data complexity

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2. Parallel-Correctness and -Boundedness of Datalog Queries

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static analysis

Query Evaluation

$$Q\colon R \bowtie S$$

relational algebra query

Query Evaluation

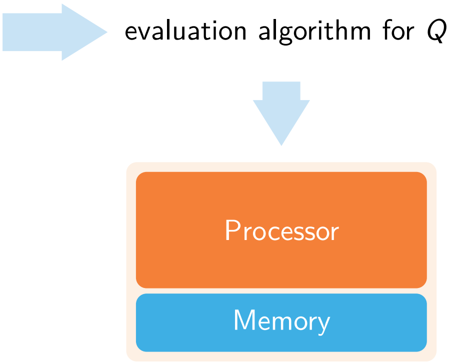
$Q\colon R \bowtie S$ → evaluation algorithm for Q

relational algebra query

Query Evaluation

$Q\colon R \bowtie S$

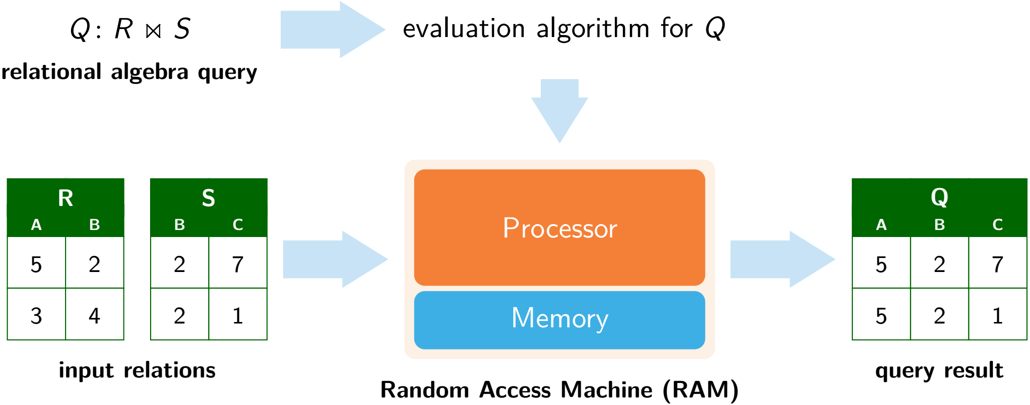
relational algebra query



evaluation algorithm for Q

Random Access Machine (RAM)

Query Evaluation



$Q\colon R \bowtie S$

relational algebra query

evaluation algorithm for Q

R	
A	B
5	2
3	4

S	
B	C
2	7
2	1

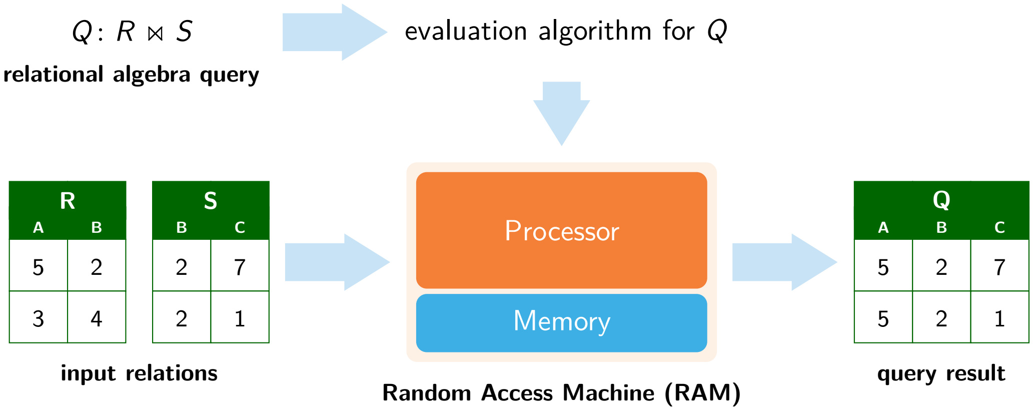
input relations

Random Access Machine (RAM)

Q		
A	B	C
5	2	7
5	2	1

query result

Query Evaluation



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relational algebra query

evaluation algorithm for Q

R	
A	B
5	2
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S	
B	C
2	7
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input relations

Processor

Memory

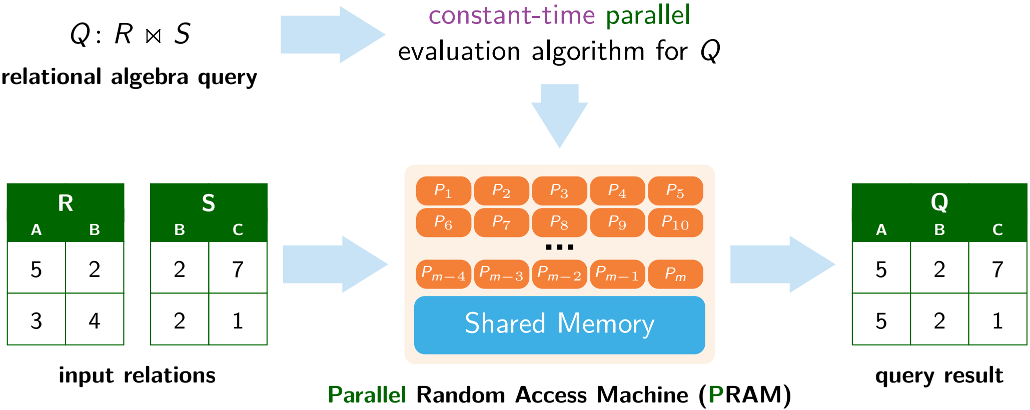
Random Access Machine (RAM)

Q		
A	B	C
5	2	7
5	2	1

query result

- **running time $\hat{=}$ number of computation steps**

Constant-Time Parallel Query Evaluation



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relational algebra query

constant-time parallel evaluation algorithm for Q

R	
A	**B**
5	2
3	4

S	
B	**C**
2	7
2	1

input relations

Parallel Random Access Machine (PRAM)

Q		
A	**B**	**C**
5	2	7
5	2	1

query result

Constant-Time Parallel Query Evaluation

$Q\colon R \bowtie S$

relational algebra query

constant-time parallel
evaluation algorithm for Q

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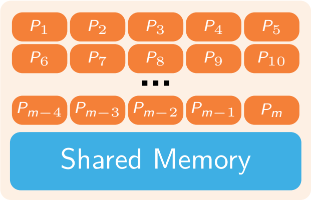


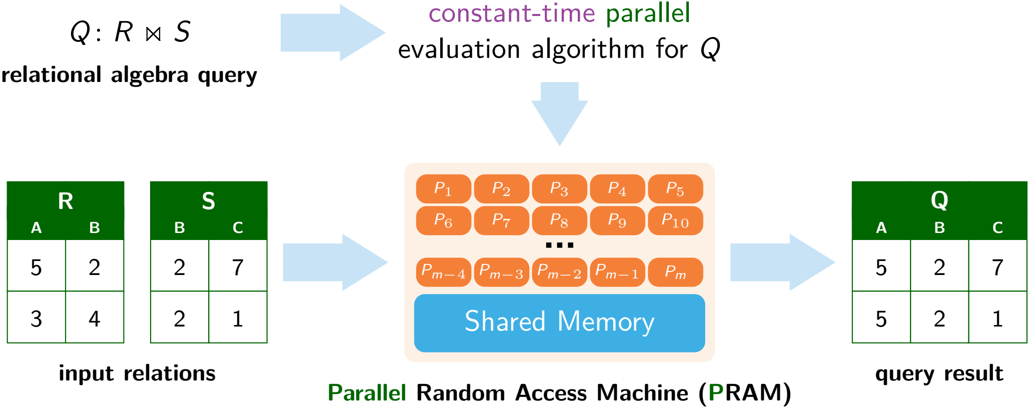
Parallel Random Access Machine (PRAM)

- **runs in constant time**
- **total number of computation steps?**

Q		
A	B	C
5	2	7
5	2	1

query result

Constant-Time Parallel Query Evaluation



$Q\colon R \bowtie S$

relational algebra query

constant-time parallel evaluation algorithm for Q

R	
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B	C
2	7
2	1

input relations

Parallel Random Access Machine (PRAM)

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A	B	C
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5	2	1

query result

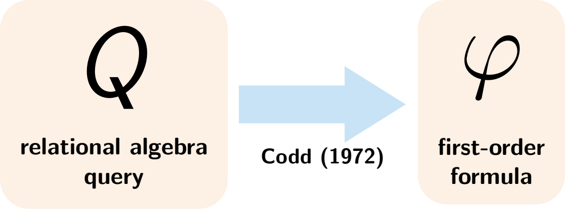
Work: Sum of computation steps of all processors

Constant-Time Parallel Evaluation

Q

relational algebra query

Constant-Time Parallel Evaluation



Q

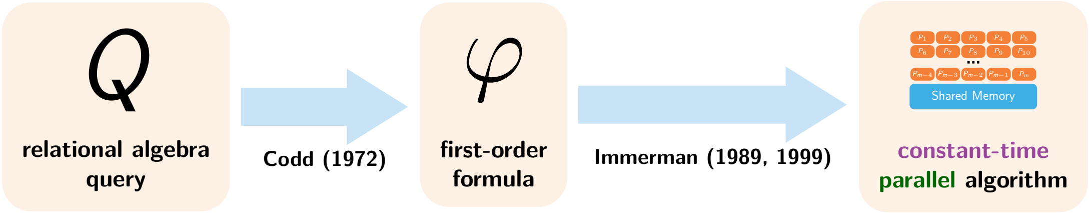
relational algebra query

Codd (1972)

φ

first-order formula

Constant-Time Parallel Evaluation



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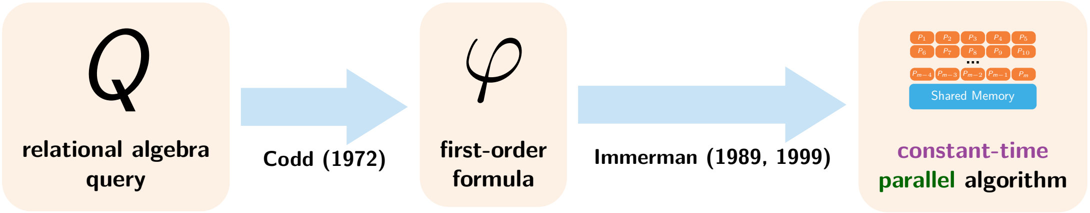
Immerman (1989, 1999)

constant-time parallel algorithm

P_1 P_2 P_3 P_4 P_5
P_6 P_7 P_8 P_9 P_{10}
P_{m-4} P_{m-3} P_{m-2} P_{m-1} P_m
Shared Memory

Constant-Time Parallel Evaluation



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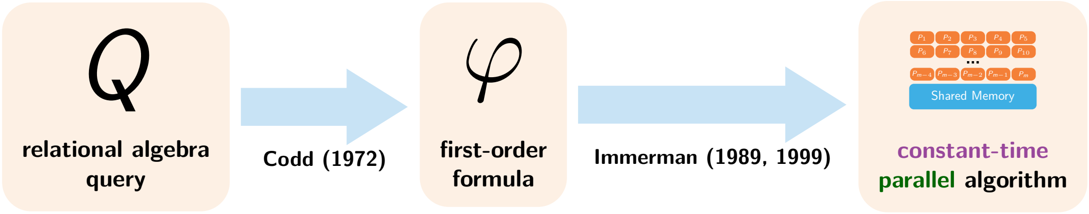
- The resulting algorithm requires work $\mathcal{O}(n^k)$
  where k is the number of variables of the formula φ (Immerman 1989, 1999).

Constant-Time Parallel Evaluation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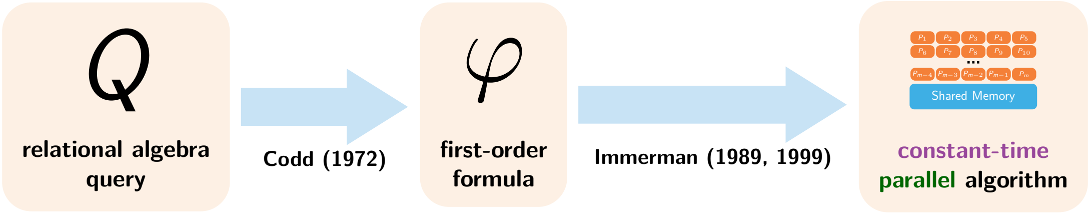

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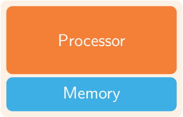
Definition

A constant time parallel algorithm is work-optimal if its work matches the running time of the best sequential algorithm.

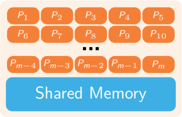
Overview of Main Results

Q

query class



classic, sequential RAM (known)

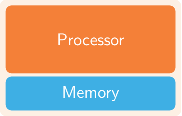


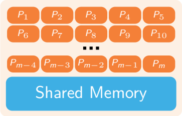
constant time, PRAM

assumptions/ data structures

Overview of Main Results

Q

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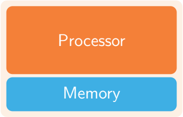
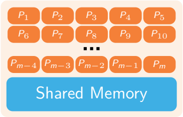
Shared Memory

query class	classic, sequential RAM (known)	constant time, PRAM	assumptions/ data structures
semi-join algebra	time $\mathcal{O}(\mathsf{IN})$	work $\mathcal{O}(\mathsf{IN}^2)$	no assumptions

Overview of Main Results

$$Q$$

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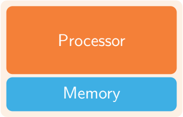
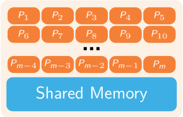
Shared Memory

query class	**classic, sequential RAM (known)**	**constant time, PRAM**	**assumptions/ data structures**
semi-join algebra	**time $\mathcal{O}(\mathsf{IN})$**	**work $\mathcal{O}(\mathsf{IN})$**	**given a dictionary for database values**

Overview of Main Results

Q

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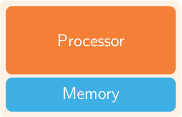

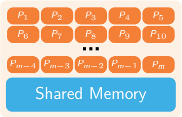
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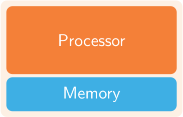
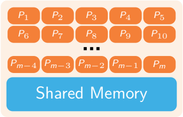
query class	classic, sequential RAM (known)	constant time, PRAM	assumptions/ data structures
semi-join algebra	time $\mathcal{O}(\textsf{IN})$	work $\mathcal{O}(\textsf{IN})$	given a dictionary for database values
acyclic conjunctive queries	time $\mathcal{O}(\textsf{IN} \cdot \textsf{OUT})$	work $\mathcal{O}((\textsf{IN} \cdot \textsf{OUT})^{1+\varepsilon})$	given a dictionary for database values

work-optimal

Overview of Main Results

Q

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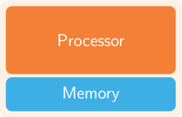

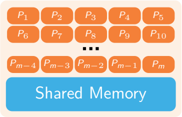
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natural join queries (worst-case framework)	time $\mathcal{O}(\prod_{i=1}^{m} \lvert R_i \rvert^{x_i} + \mathsf{IN})$		

Overview of Main Results

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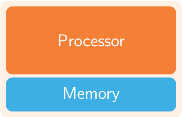

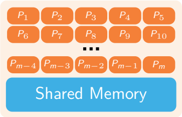

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Dictionaries

- dictionary-based compressed databases
- for instance, used for query optimisation (e.g. Chen, Gehrke, and Korn 2001)

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Example

Movies	
Title	Year
True Romance	1993
Jurassic Park	1993
The Godfather	1972

Dictionaries

- dictionary-based compressed databases
- for instance, used for query optimisation (e.g. Chen, Gehrke, and Korn 2001)

Example

Movies	
Title	Year
True Romance	1993
Jurassic Park	1993
The Godfather	1972

→

Movies	
Title	Year
1	4
2	4
3	5

+

Dictionary	
Key	Value
1	True Romance
2	Jurassic Park
3	The Godfather
4	1993
5	1972

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Settings for Constant-Time Parallel Evaluation

Dictionary Setting

- A dictionary for the database is available

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General Setting

- A single processor can test for equivalence in constant time
- Lemma: A dictionary can be computed in constant-time with work $\mathcal{O}(\mathsf{IN}^2)$.

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Dictionary Setting

- A dictionary for the database is available

General Setting

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- Lemma: A dictionary can be computed in constant-time with work $\mathcal{O}(\mathsf{IN}^2)$.

Ordered Setting

- There is a linear order on the domain values
- A single processor can test for less than in constant time
- Lemma: For every $\varepsilon > 0$, a dictionary can be computed in constant-time with work $\mathcal{O}(\mathsf{IN}^{1+\varepsilon})$, given suitably ordered arrays for the database relations.

Settings

1. Work-Efficient Constant-Time Parallel Query Evaluation
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data complexity

2. Parallel-Correctness and -Boundedness of Datalog Queries
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static analysis

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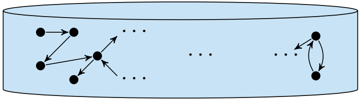
Distributed Evaluation

global database



Query

- transitive closure T
- Datalog program

$$T(x,y) \leftarrow E(x,y)$$
$$T(x,z) \leftarrow T(x,y),\ E(y,z)$$

- recursive evaluation (fixed point computation)

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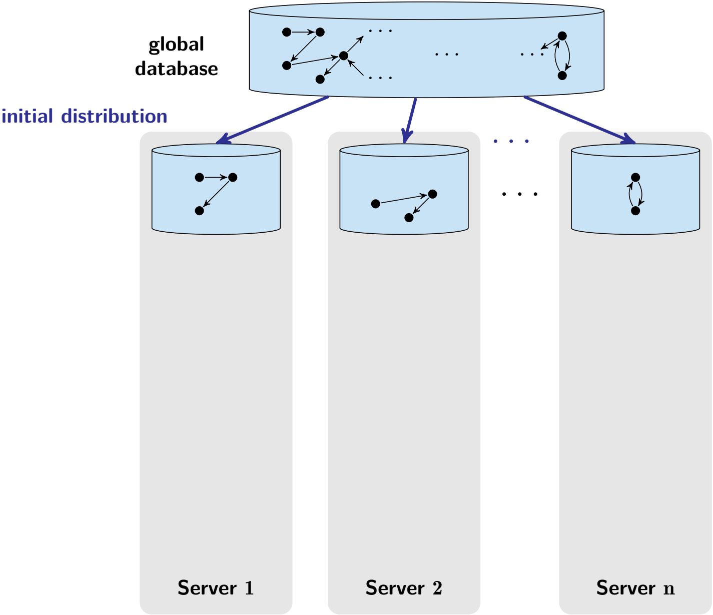

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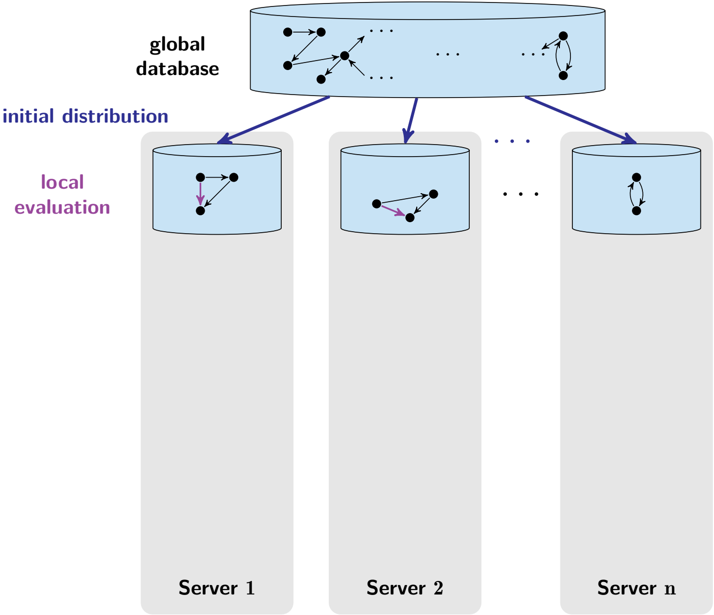

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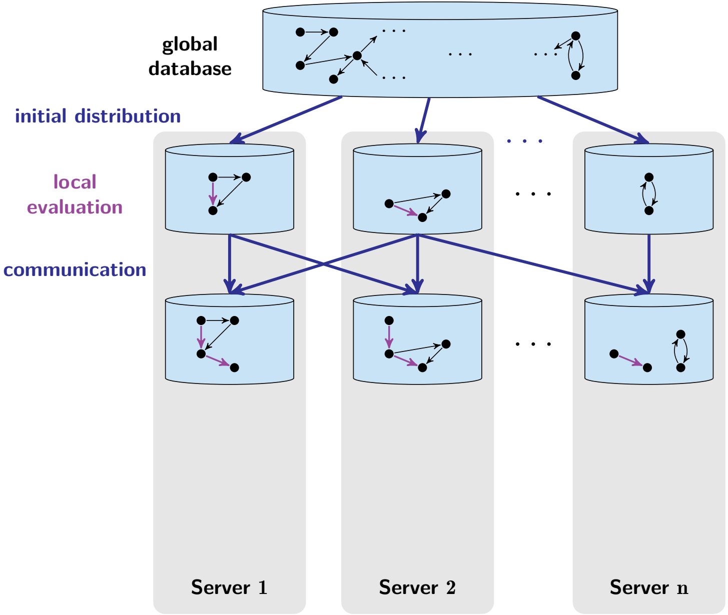

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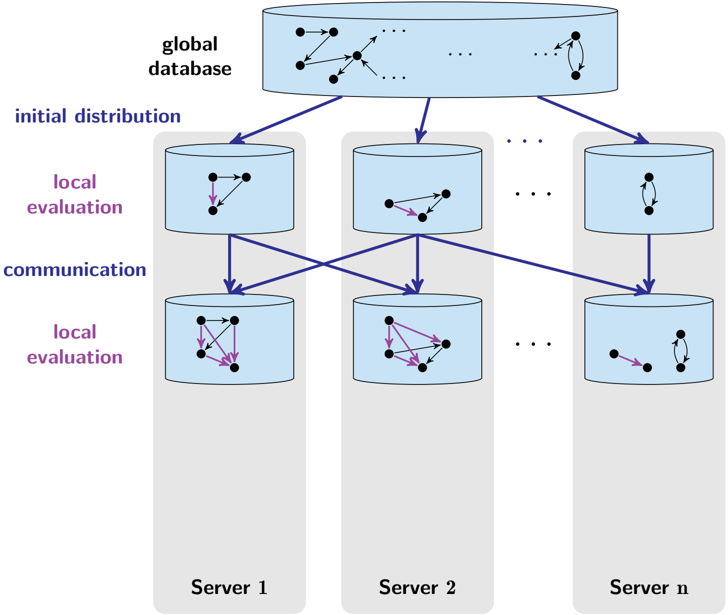

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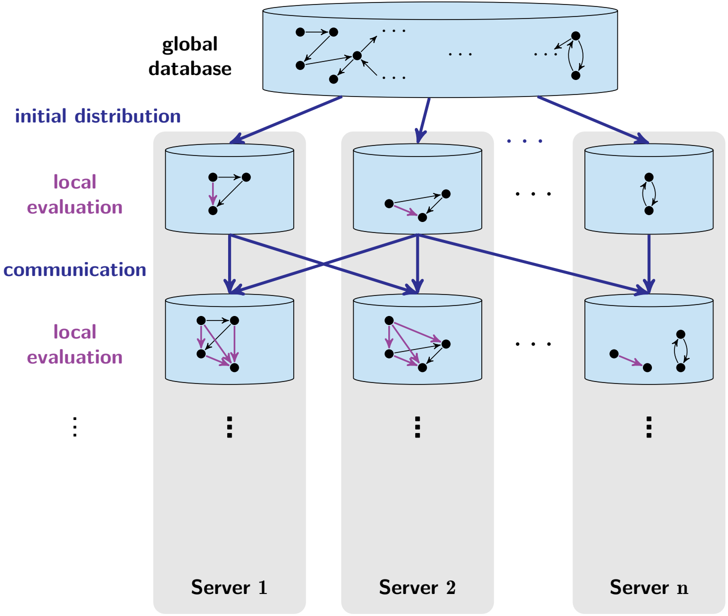

Distributed Evaluation

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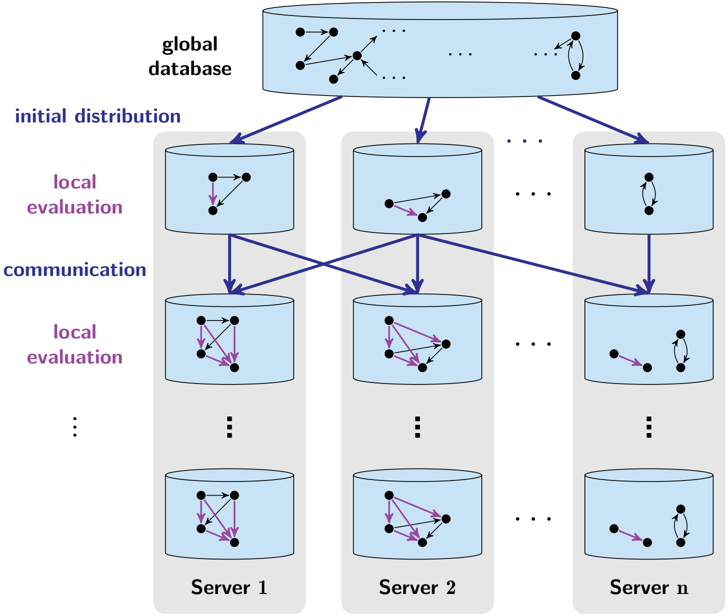

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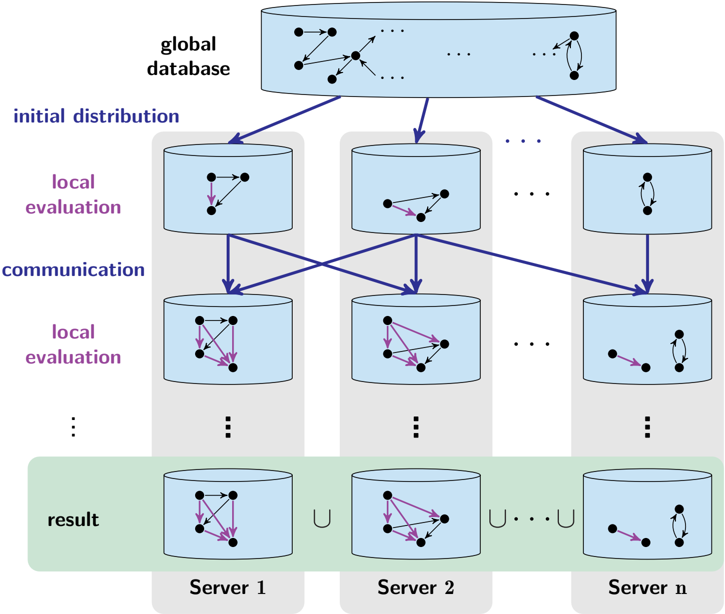
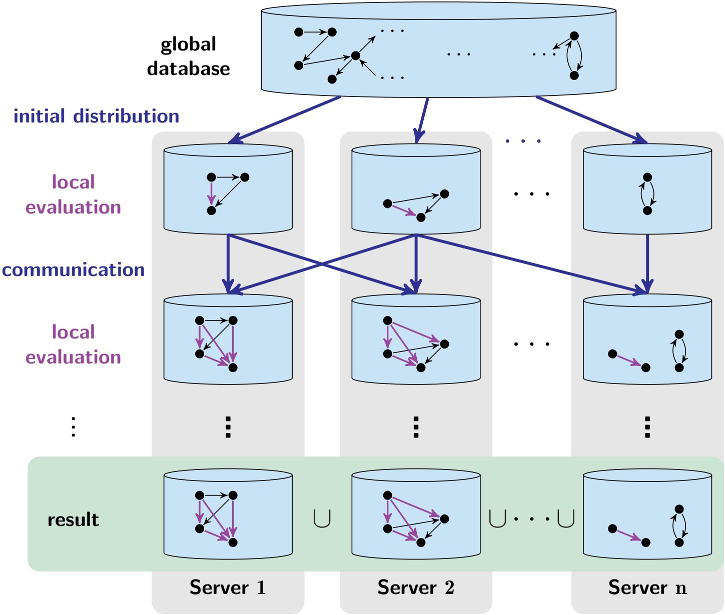
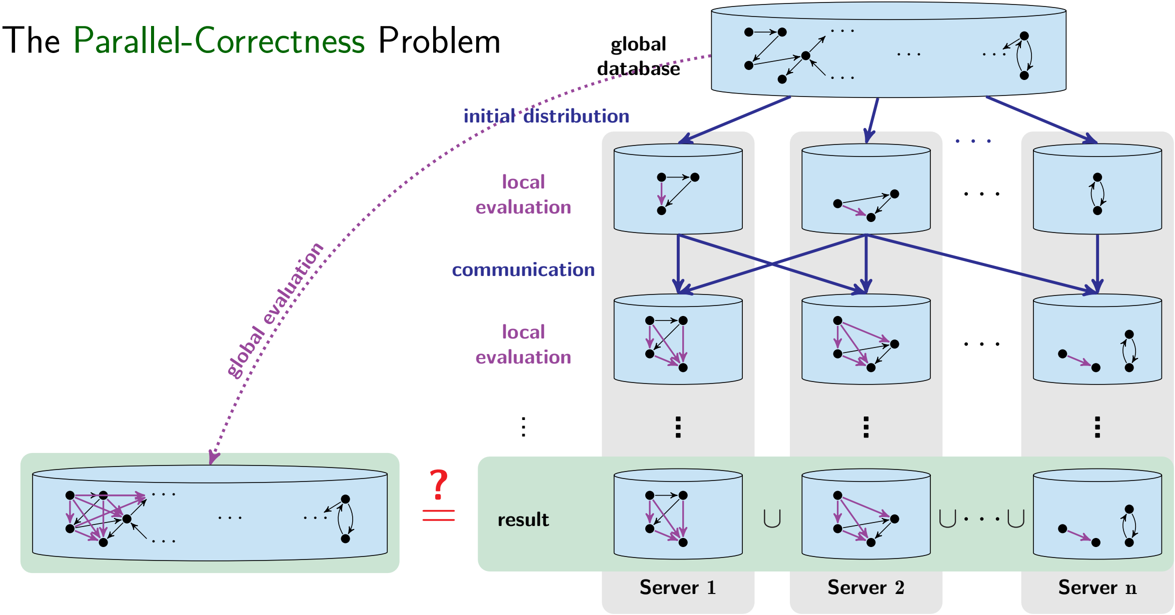


Distributed Evaluation

Massively Parallel Communication (MPC)
model
(Beame, Koutris, and Suciu 2017)



The Parallel-Correctness Problem



The Parallel-Correctness Problem

Parallel-Correctness Problem

Input:

- Datalog program
- distribution policy
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Question:

Do distributed and global evaluation yield the same result for all databases?

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Parallel-correctness for general Datalog programs is undecidable.

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- Even for “simple” policies:
  - only two servers
  - all but one relations are distributed to both servers
  - no communication

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- Datalog program
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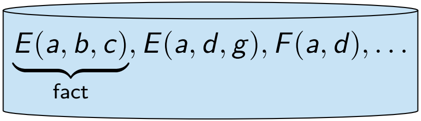
Parallel-correctness for general Datalog programs is undecidable.

- Even for “simple” policies:
  - only two servers
  - all but one relations are distributed to both servers
  - no communication
- Is there a fragment of Datalog for which parallel-correctness is decidable?
- How to specify distribution and communication policies?

Basics

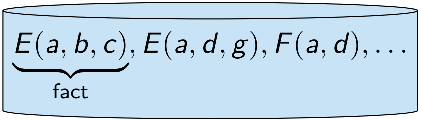
Relational databases



$$\underbrace{E(a,b,c)}_{\text{fact}}, E(a,d,g), F(a,d), \dots$$

Basics

Relational databases



$$\underbrace{E(a,b,c)}_{\text{fact}}, E(a,d,g), F(a,d), \ldots$$

Datalog programs consist of rules

$$\underbrace{T(x,y)}_{\text{head}} \leftarrow \underbrace{E(x,y,z), \overbrace{R(x,v)}^{\text{atom}}}_{\text{body}}.$$

- relation symbol of the head does not occur in the database
- rules can be recursive
- no negation

Parallel-Correctness and Containment

Undecidability of parallel-correctness results from the containment problem

... and containment is undecidable for general Datalog

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Undecidability of parallel-correctness results from the containment problem

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general Datalog

monadic Datalog

only unary head atoms

Example:
$R(x) \leftarrow S(x), E(y, z, u)$

Containment is decidable for monadic Datalog

Parallel-Correctness and Containment

Undecidability of parallel-correctness results from the containment problem

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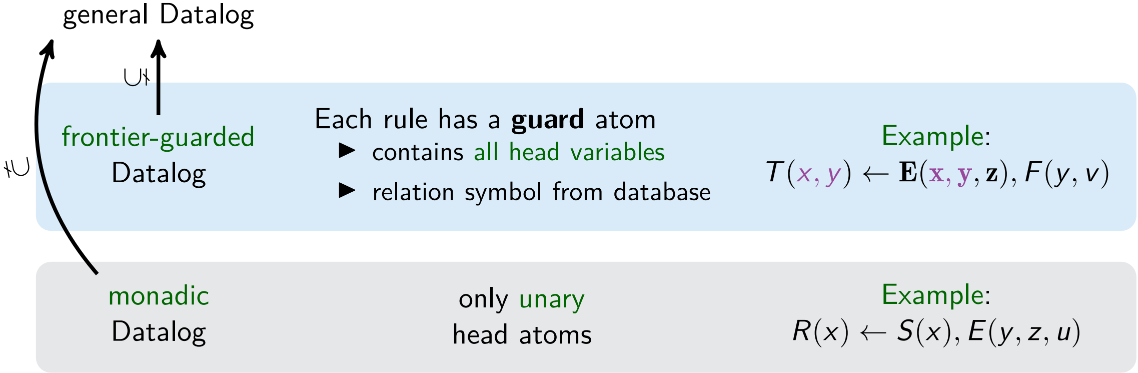

general Datalog

frontier-guarded Datalog

Each rule has a **guard** atom

- contains all head variables
- relation symbol from database

Example:
$T(x, y) \leftarrow \mathbf{E}(\mathbf{x}, \mathbf{y}, \mathbf{z}), F(y, v)$

monadic Datalog

only unary head atoms

Example:
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Containment is decidable for monadic Datalog and frontier-guarded Datalog

Parallel-Correctness and Containment

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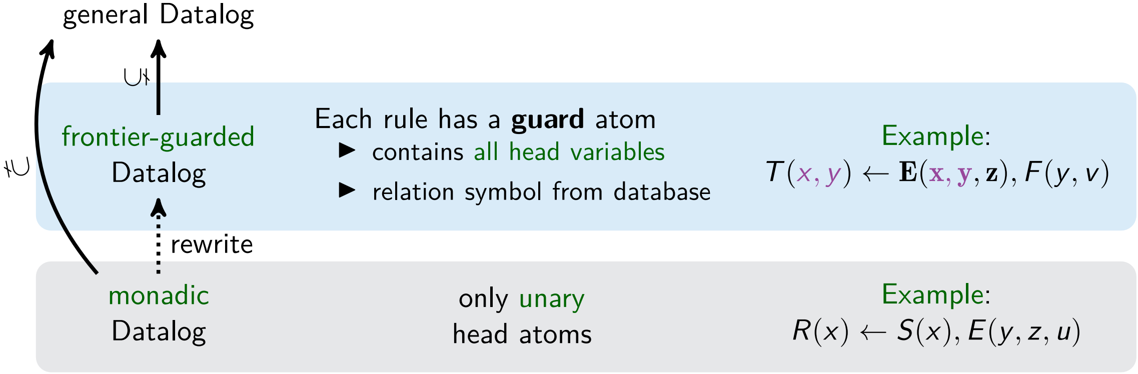

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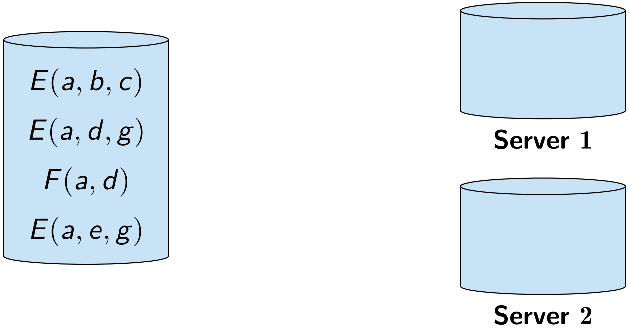
Distribution Policies

Idea: Use hash functions $h_1, \ldots, h_k$ fast, evenly distribution



$E(a, b, c)$

$E(a, d, g)$

$F(a, d)$

$E(a, e, g)$

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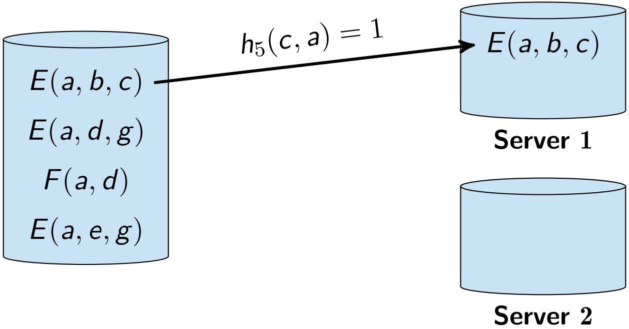

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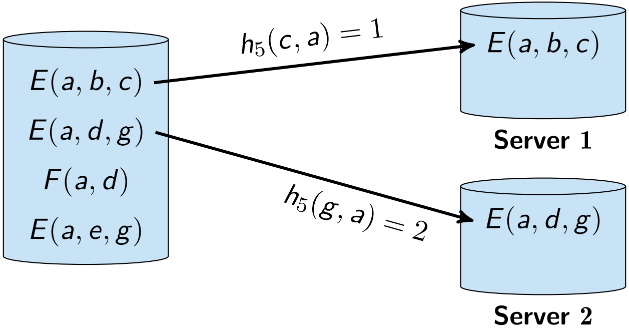


$E(a, b, c)$

$E(a, d, g)$

$F(a, d)$

$E(a, e, g)$

$h_5(c, a) = 1$

$h_5(g, a) = 2$

$E(a, b, c)$

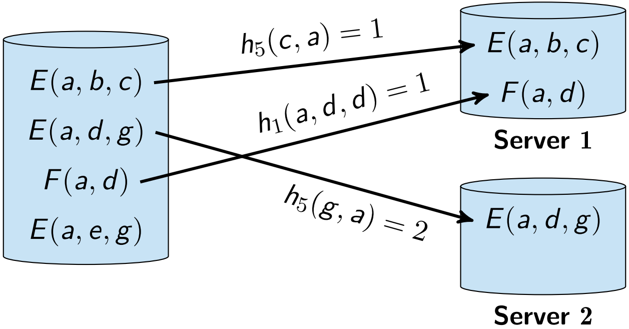
Server 1

$E(a, d, g)$

Server 2

Distribution Policies

Idea: Use hash functions $h_1, \ldots, h_k$ fast, evenly distribution



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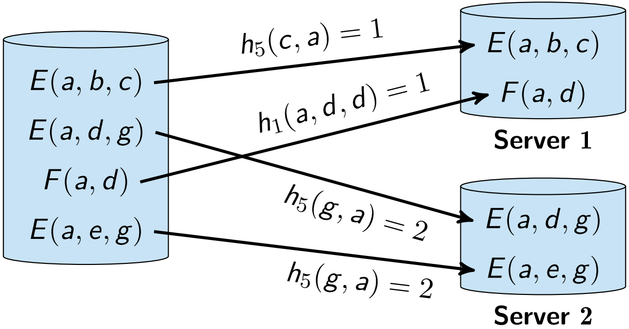

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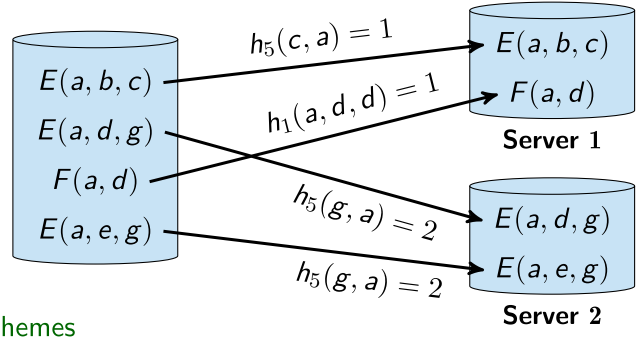


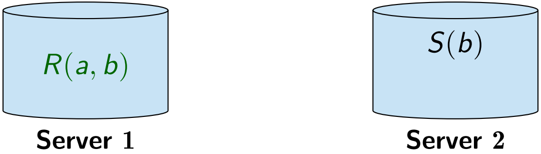
Here: Hash policy schemes

- describes how hash functions are applied
- defines class of hash functions

Communication Policies

Data-Moving Distribution Constraints

$$\underbrace{R(x,y)@\lambda, S(y)@\kappa}_{\text{body}} \rightarrow \underbrace{R(x,y)@\kappa}_{\text{head}}$$



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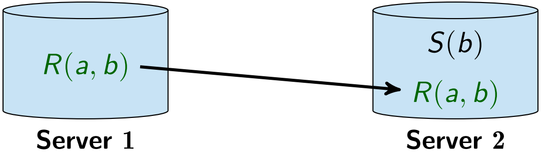


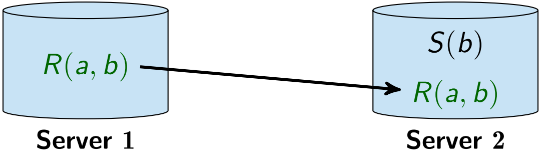
Communication Policies

Data-Moving Distribution Constraints

$$\underbrace{R(x,y)@\lambda, S(y)@\kappa}_{\text{body}} \rightarrow \underbrace{R(x,y)@\kappa}_{\text{head}}$$

Both $R(x,y)$ and κ occur in the body.

- No creation of facts
- No creation of servers



Parallel-Correctness: Main Results

Datalog fragment	hash policy schemes and data-moving distribution constraints
frontier-guarded	
monadic	

Parallel-Correctness: Main Results

Datalog fragment	hash policy schemes and data-moving distribution constraints
frontier-guarded	undecidable*
monadic	undecidable*

*mainly contributed by my co-authors to the ICDT'19 paper

Parallel-Correctness: Main Results

Datalog fragment	hash policy schemes and	...with polynomial communication property	
	data-moving distribution constraints	syntactical fragment	changed semantics
frontier-guarded	undecidable*		
monadic	undecidable*		

Polynomial Communication Property

- The amount of communication without any local computation in between is bounded polynomially

*mainly contributed by my co-authors to the ICDT'19 paper

Parallel-Correctness: Main Results

Datalog fragment	hash policy schemes and	…with polynomial communication property	
	data-moving distribution constraints	syntactical fragment	changed semantics
frontier-guarded	undecidable*	2ExpTime-complete	2ExpTime-complete
monadic	undecidable*		

Theorem

Parallel-correctness for frontier-guarded Datalog,

- *hash policy schemes, and*
- *data-moving distribution constraints*
- *with the polynomial communication property*

is 2ExpTime-complete.

*mainly contributed by my co-authors to the ICDT'19 paper

Parallel-Correctness: Main Results

Datalog fragment	hash policy schemes and data-moving distribution constraints	…with polynomial communication property	
		syntactical fragment	changed semantics
frontier-guarded	undecidable*	2ExpTime-complete	2ExpTime-complete
monadic	undecidable*	in 2ExpTime	in 2ExpTime

Reminder: Every monadic Datalog query can be translated into an equivalent frontier-guarded Datalog query.

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Parallel-Correctness: Main Results

Datalog fragment	hash policy schemes and	…with polynomial communication property	
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frontier-guarded	undecidable[*]	2ExpTime-complete	2ExpTime-complete
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Parallel-Correctness: Main Results

Datalog fragment	hash policy schemes and data-moving distribution constraints	…with polynomial communication property	
		syntactical fragment	changed semantics
frontier-guarded	undecidable*	2ExpTime-complete	2ExpTime-complete
monadic	undecidable*	open	undecidable*

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Parallel-Boundedness

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There is a bound $r \in \mathbb{N}$ such that

- for every database
- no new facts are computed
- after r communication rounds.

- Local computations may be unbounded!

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Theorem

Parallel-boundedness for frontier-guarded Datalog programs,

- *hash policy schemes, and*
- *data-moving distribution constraints with the polynomial communication property*

that are parallel-correct is 2ExpTime-*complete.*

Settings

1. Work-Efficient Constant-Time Parallel Query Evaluation
   Preliminary results published at ICDT'23, Ioannina, Greece
   (Keppeler, Schwentick, and **S.** 2023)

data complexity

---

2. Parallel-Correctness and -Boundedness of Datalog Queries
   ICDT'19, Lisbon, Portugal (Neven, Schwentick, **S.**, and Vandevoort 2019)

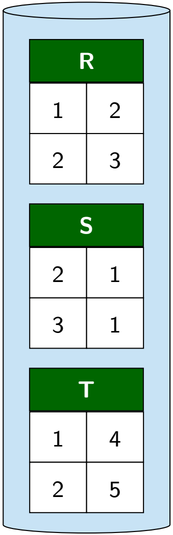
static analysis

---

3. Structurally Simple Rewritings
   ICDT'22, Edinburgh, UK (Geck, Keppeler, Schwentick, and **S.** 2022)
   LMCS Journal (Geck, Keppeler, Schwentick, and **S.** 2023)

static analysis

Rewritings



R	
1	2
2	3

S	
2	1
3	1

T	
1	4
2	5

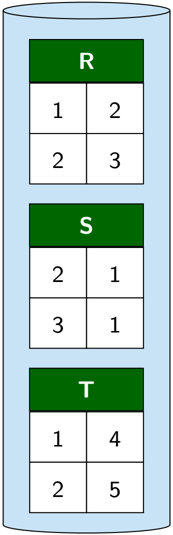
relational database

Rewritings

Query $H(x, w) \leftarrow R(x, y),\ S(y, z),\ T(z, w)$

Conjunctive Query

single, non-recursive rule



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no direct access

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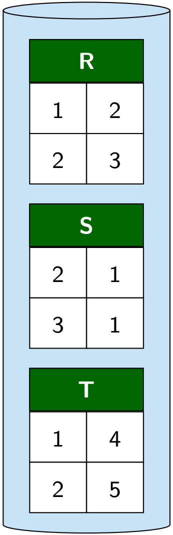

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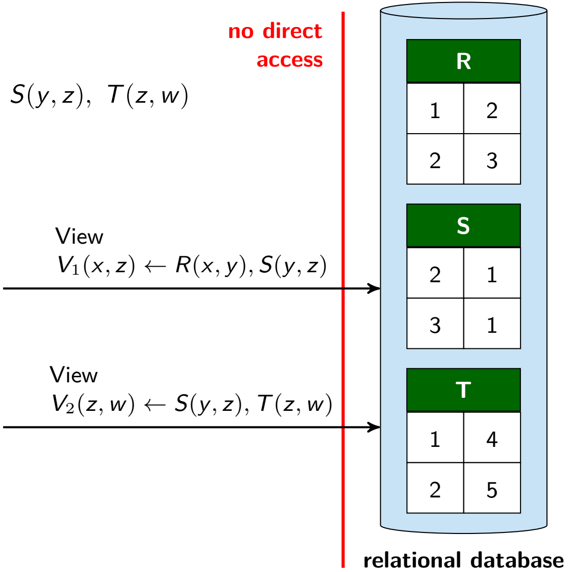

no direct access

View
$V_1(x, z) \leftarrow R(x, y), S(y, z)$

View
$V_2(z, w) \leftarrow S(y, z), T(z, w)$

R	
1	2
2	3

S	
2	1
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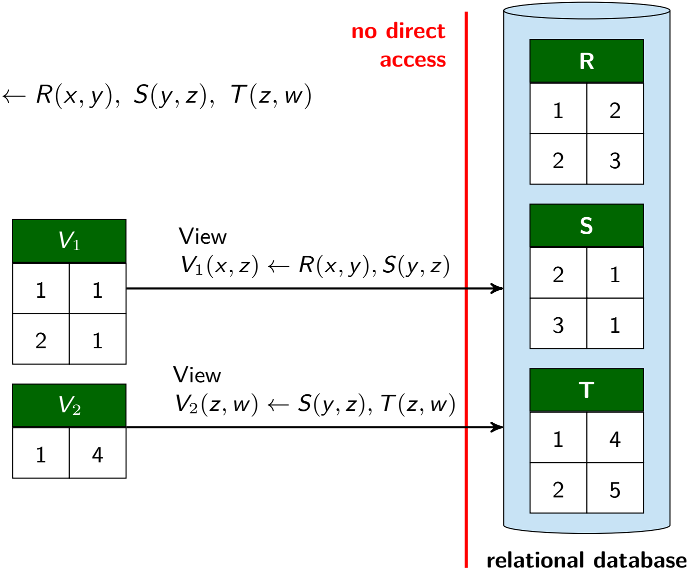
Query $H(x, w) \leftarrow R(x, y),\ S(y, z),\ T(z, w)$



View
$V_1(x, z) \leftarrow R(x, y), S(y, z)$

View
$V_2(z, w) \leftarrow S(y, z), T(z, w)$

V_1	
1	1
2	1

V_2	
1	4

R	
1	2
2	3

S	
2	1
3	1

T	
1	4
2	5

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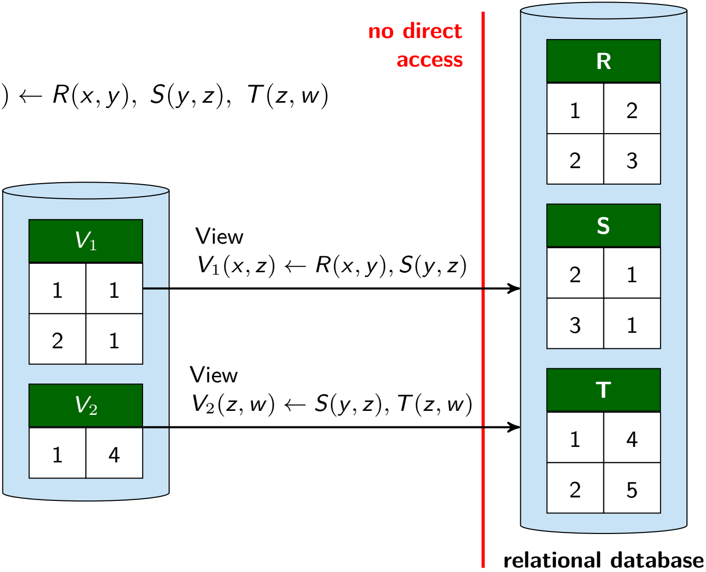
Query $H(x, w) \leftarrow R(x, y),\ S(y, z),\ T(z, w)$



no direct access

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View $V_2(z, w) \leftarrow S(y, z), T(z, w)$

V_1	
1	1
2	1

V_2	
1	4

R	
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S	
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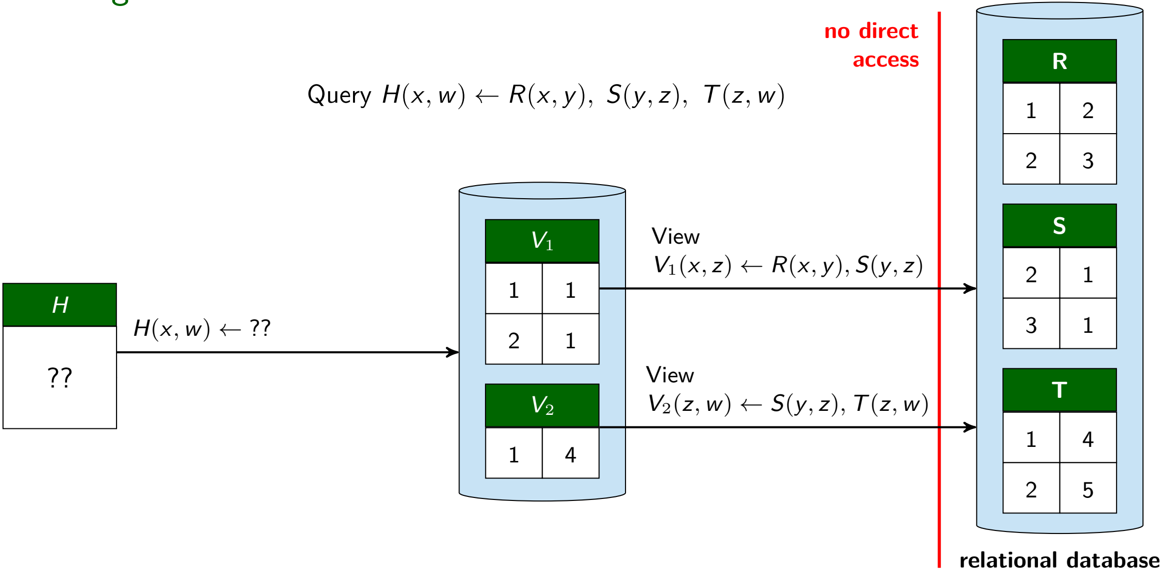
Query $H(x,w) \leftarrow R(x,y),\ S(y,z),\ T(z,w)$



H
??

$H(x,w) \leftarrow ??$

V_1	
1	1
2	1

V_2	
1	4

View
$V_1(x,z) \leftarrow R(x,y), S(y,z)$

View
$V_2(z,w) \leftarrow S(y,z), T(z,w)$

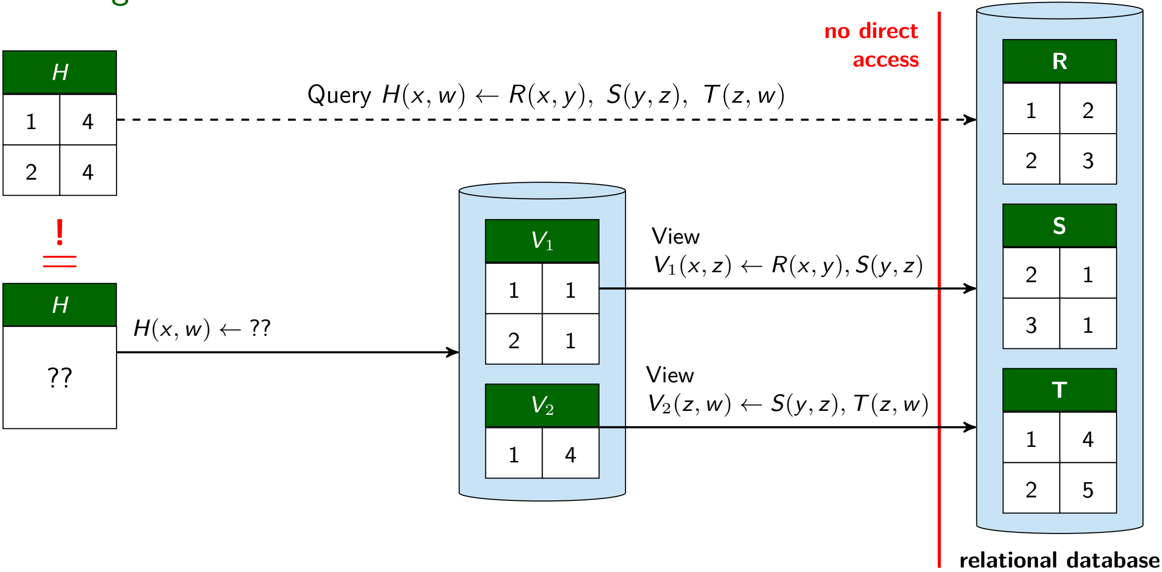
R	
1	2
2	3

S	
2	1
3	1

T	
1	4
2	5

relational database

Rewritings



H	
1	4
2	4

Query $H(x,w) \leftarrow R(x,y),\ S(y,z),\ T(z,w)$

H
??

$H(x,w) \leftarrow ??$

V_1	
1	1
2	1

V_2	
1	4

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View $V_2(z,w) \leftarrow S(y,z), T(z,w)$

R	
1	2
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S	
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3	1

T	
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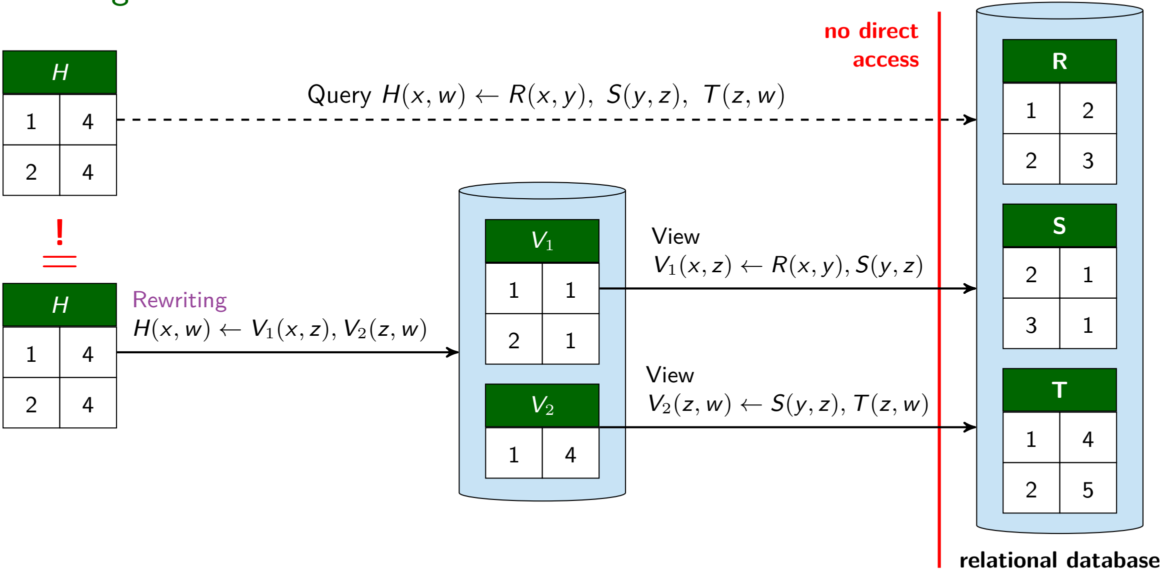
Rewritings



H	
1	4
2	4

Query $H(x,w) \leftarrow R(x,y),\ S(y,z),\ T(z,w)$

no direct access

$\overset{!}{=}$

H	
1	4
2	4

Rewriting
$H(x,w) \leftarrow V_1(x,z), V_2(z,w)$

V_1	
1	1
2	1

V_2	
1	4

View
$V_1(x,z) \leftarrow R(x,y), S(y,z)$

View
$V_2(z,w) \leftarrow S(y,z), T(z,w)$

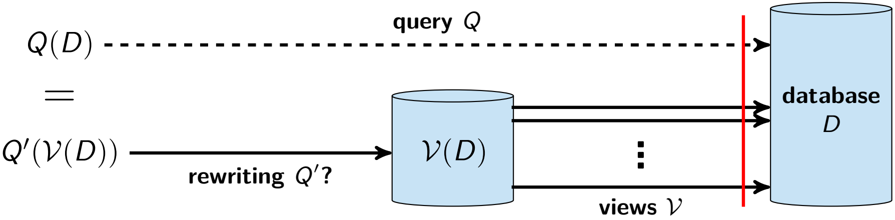
R	
1	2
2	3

S	
2	1
3	1

T	
1	4
2	5

relational database

The Rewriting Problem



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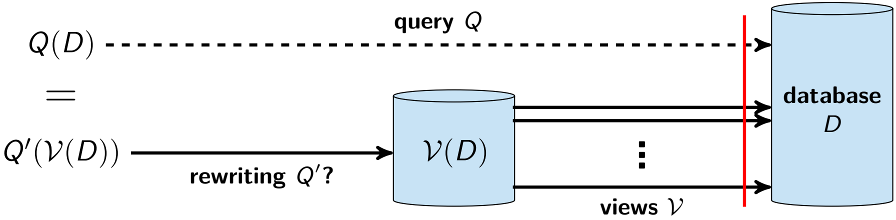

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Input:

- conjunctive query Q
- set $\mathcal{V}$ of views

Question:

Is there a rewriting for Q with respect to $\mathcal{V}$?

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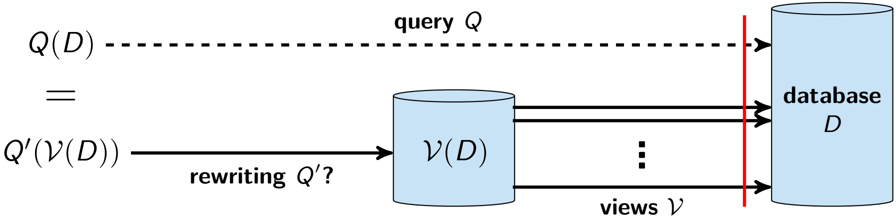

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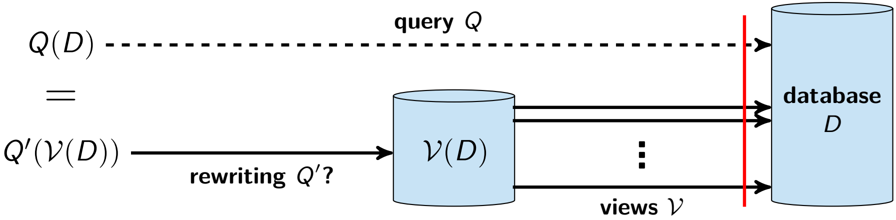

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→ Restrict everything to structurally simple queries

Acyclic Conjunctive Queries

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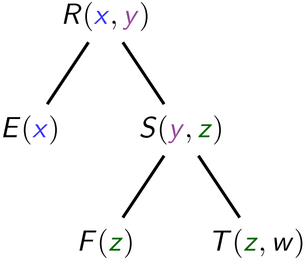
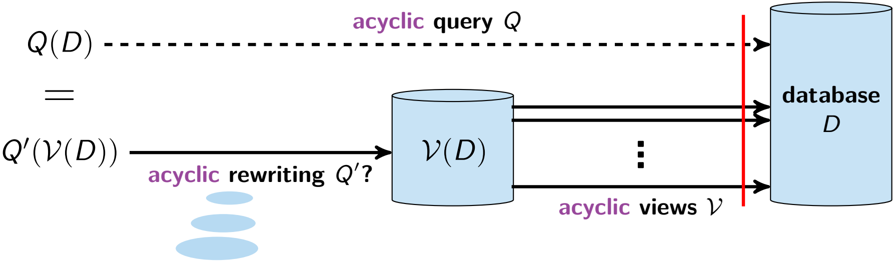
Example

$H(x, y) \leftarrow R(x, y), S(y, z), F(z), E(x), T(z, w)$ is acyclic



For every variable:
the induced subgraph is connected

Complexity of the Acyclic Rewriting Problem



If the query is acyclic, we would like the rewriting to be acyclic as well

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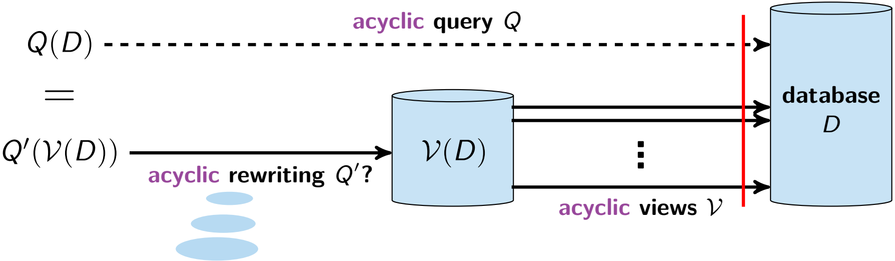

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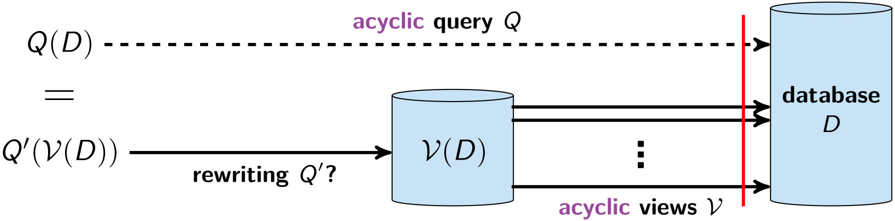

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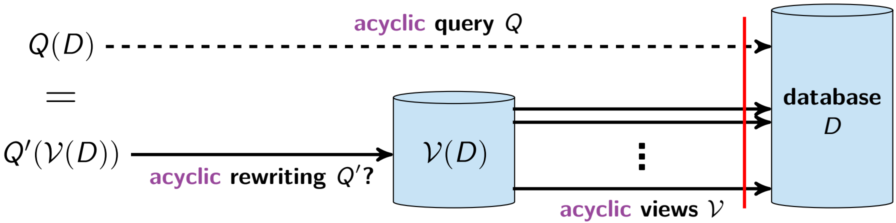
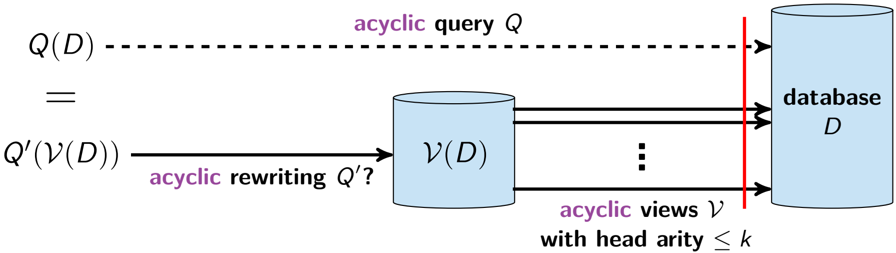


Theorem

If the query is acyclic and there is any rewriting, there is an acyclic rewriting.

Complexity of the Acyclic Rewriting Problem



Theorem

For every $k \geq 0$, the acyclic rewriting problem for

- *acyclic queries and*
- *views defined by acyclic queries with head arity at most k*

is in polynomial time.

Rewritings: Main Results

Views	Query	Rewriting	Restriction of views	arity of database relations	
				is $\le k, k \in \mathbb{N}_0$	unbounded
acyclic	acyclic	acyclic	no restriction	NP-complete for $k \geq 3$	
acyclic	acyclic	acyclic	head arity $\leq \ell$ $\ell \in \mathbb{N}_0$	polynomial time	
acyclic	acyclic	acyclic	weak head arity $\leq \ell$ $\ell \in \mathbb{N}_0$	polynomial time	
free-connex acyclic	acyclic	acyclic	no restriction	polynomial time	open
hierarchical	hierarchical	hierarchical	no restriction	NP-complete for $k \geq 3$	
q-hierarchical	q-hierarchical	q-hierarchical	no restriction	polynomial time	open

Conclusion

1. Work-Efficient Constant-Time Parallel Query Evaluation
   - Transforming classical algorithms into constant-time parallel algorithms

data complexity

2. Parallel-Correctness and -Boundedness of Datalog Queries
   - Deciding whether query evaluation is correct

static analysis

3. Structurally Simple Rewritings
   - Preserving structural properties of queries under access restriction

static analysis

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