Conjunctive Queries with Free Access Patterns under Updates

Ahmet Kara, Milos Nikolic, Dan Olteanu, Haozhe Zhang

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Scenario

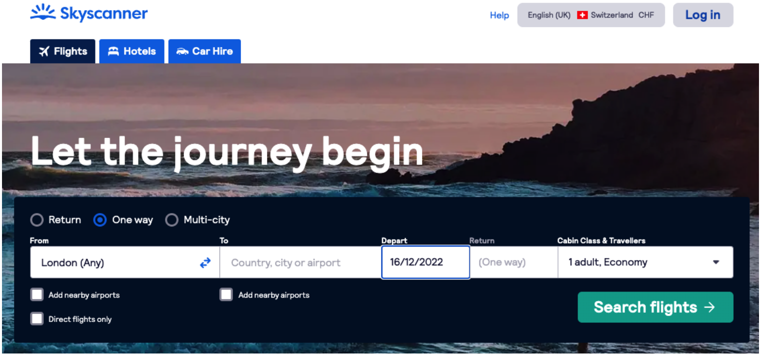

Figure: Flight Booking Interface

Scenario

The flight booking company has a database with the two relations:

- `Flight: (FlightNo, DEPAirport, ARRAirport, Date, Price)`
- `Airport: (Airport, Name, City)`

List the flights in the database with the airport information:

```
FlightSearch(FlightNo, DEPCity, ARRCity, Date) :-
    Flight(FlightNo, DEPAirport, ARRAirport, Date, Price),
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List the flights from **London** to **Zurich** on **1st January 2023**:

```
FlightSearch(FlightNo, "London", "Zurich", "2023-01-01") :-
    Flight(FlightNo, DEPAirport, ARRAirport, "2023-01-01", Price),
    DEPAirport(DEPAirport, Name, "London"),
    ARRAirport(ARRAirport, Name, "Zurich").
```

Challenges

Query with parameters %DEPCity, %ARRCity and %Date:

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FlightSearch(FlightNo, "%DEPCity", "%ARRCity", "%Date") :-
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- The database is subject to frequent updates, e.g., new flights are added, existing flights are cancelled, etc.

Conjunctive Queries with Free Access Patterns

We formalize such data access by ***Conjunctive Queries with Free Access Patterns*** (CQAPs)

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- Free variables are partitioned into ***input*** and ***output*** variables
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- Also called *parameterized queries* or *prepared statements* in DBMS

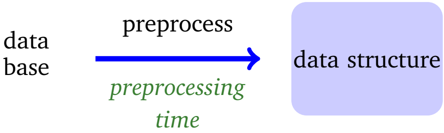
Problem Setting

We consider the problem of **fully dynamic evaluation** for **CQAPs**:

- Maintaining the database under tuple updates (inserts or deletes)
- Answering access requests

Dynamic Query Evaluation Framework

Given a CQAP $Q(\mathcal{O} \mid \mathcal{I})$, compute a data structure that supports answering the access requests and maintains it under updates.



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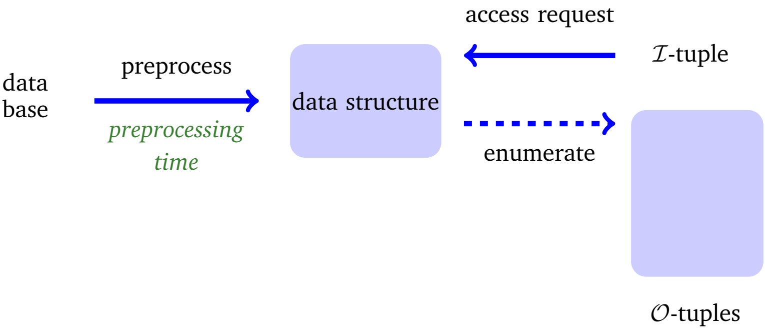

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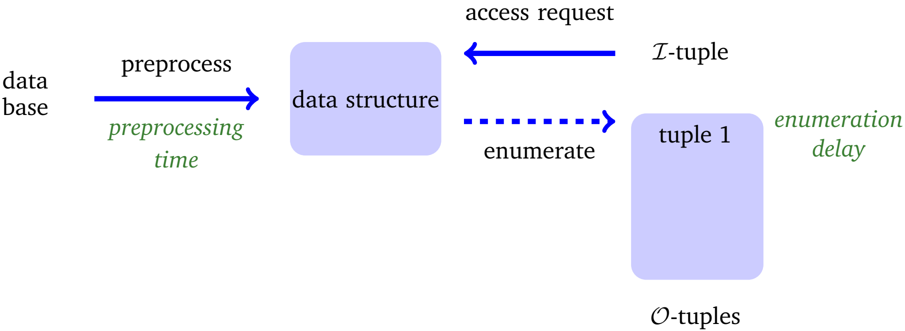

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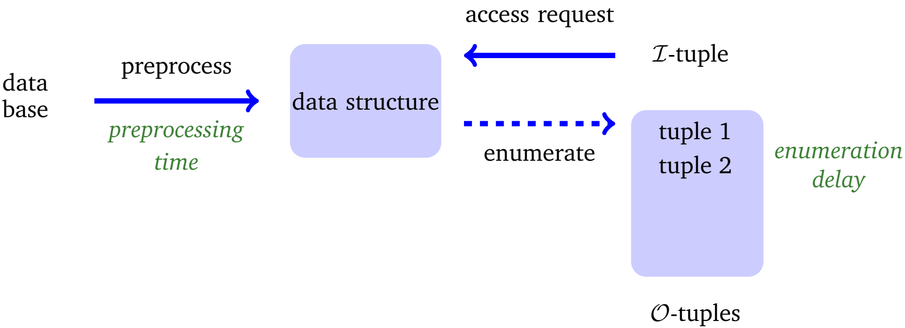

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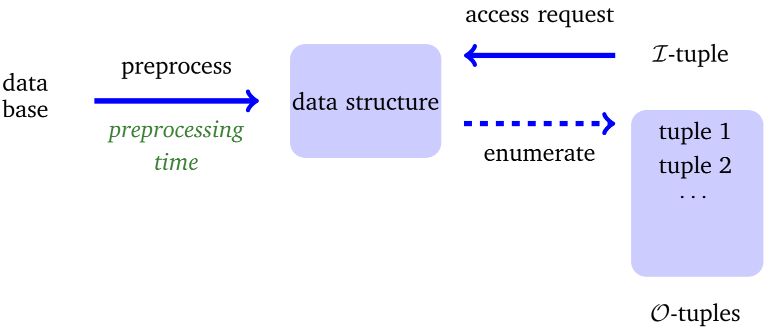

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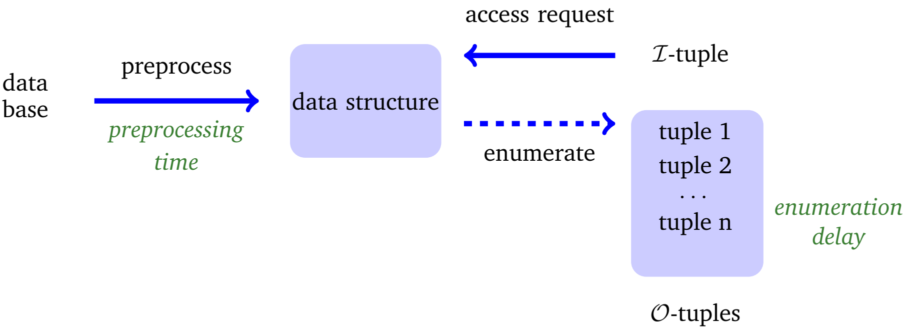

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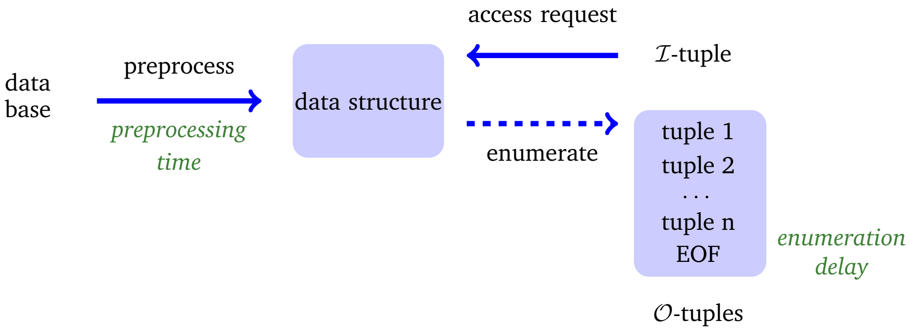

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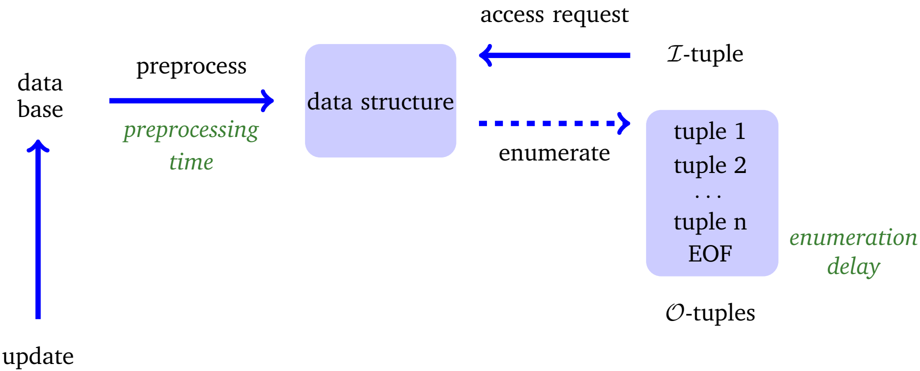

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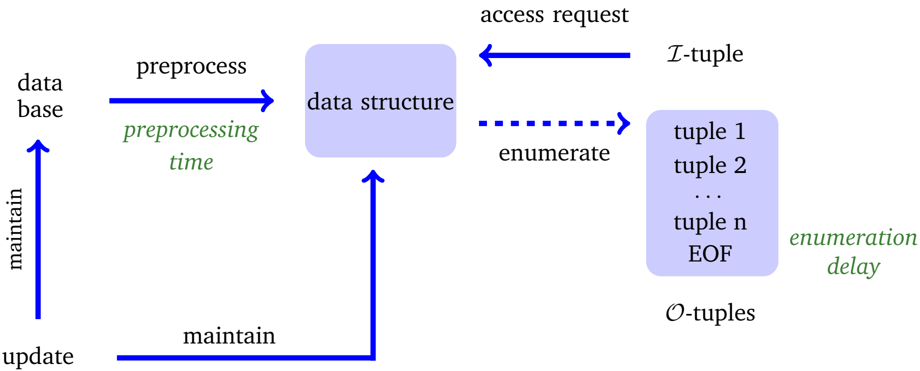

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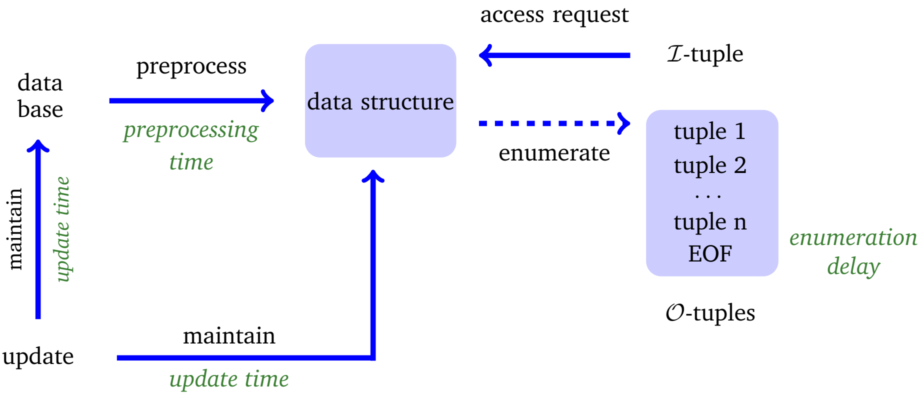
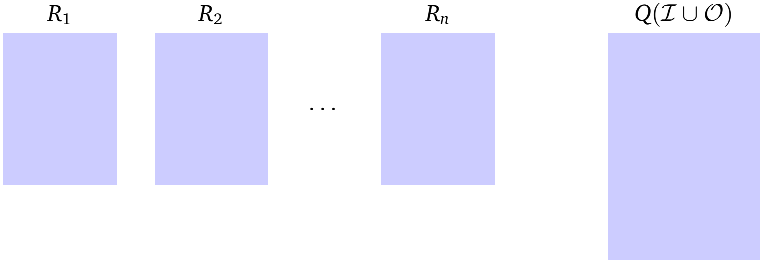


Mainstream Approaches

Eager approach:

- Preprocessing: Compute the **full result** and create an index for the access pattern
- Enumeration: Lookup the index and return the result
- Update: Maintain the full result and the index under each update

Mainstream Approaches: Eager Approach



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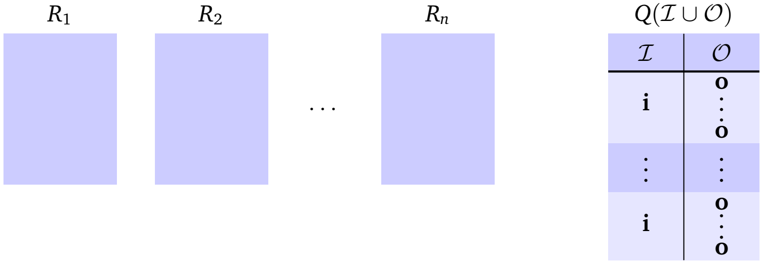

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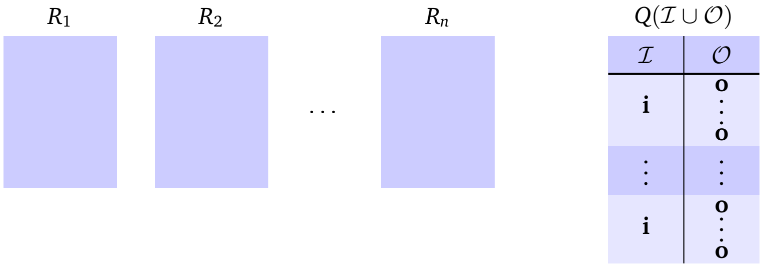

Enumeration: Lookup the index and output the result tuple by tuple

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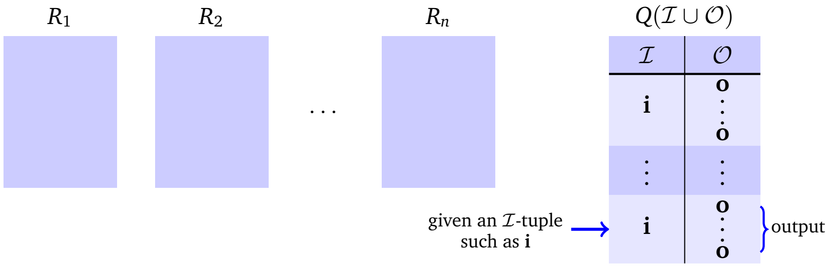

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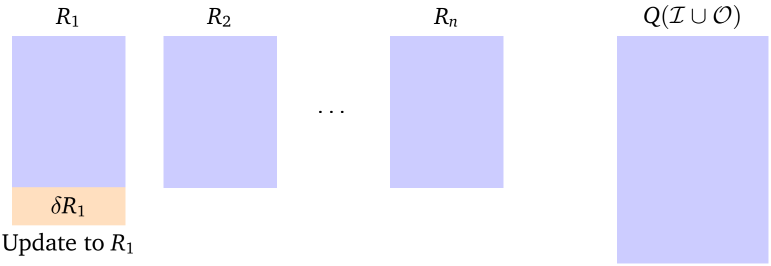

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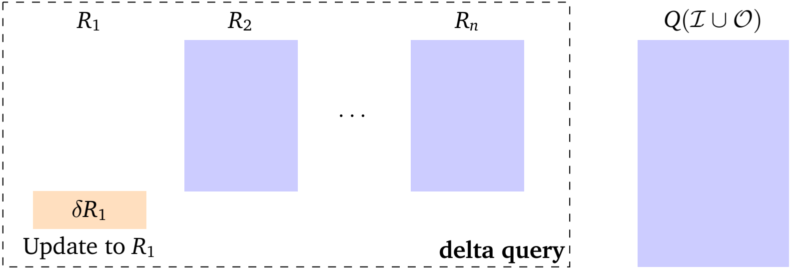

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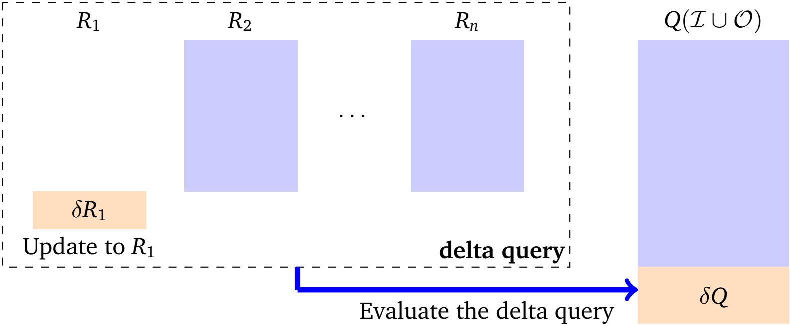

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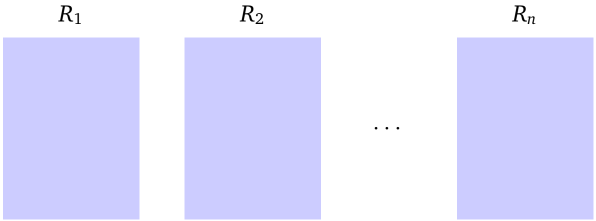
Mainstream Approaches

Lazy approach:

- **No preprocessing**
- Enumeration: Upon each access request, set the input variables to constants and evaluate the residual query
- Update: Maintain only the base relations

Mainstream Approaches: Lazy Approach



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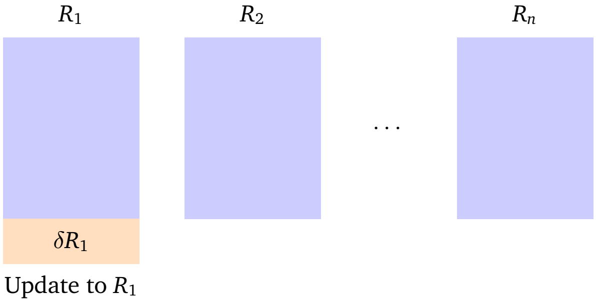

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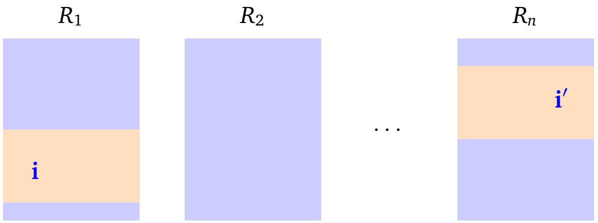

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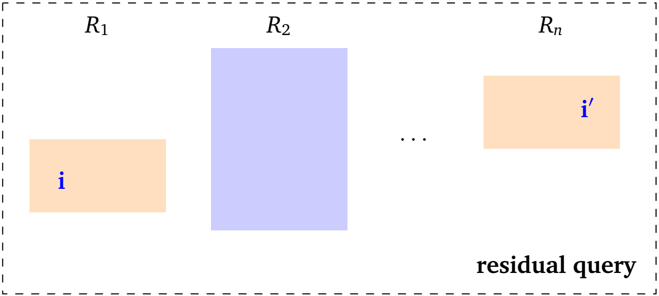

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We have discussed the two mainstream approaches in the previous slides.

We propose two algorithms that **improve** the mainstream approaches:

1. **Avoiding full materialization** in the eager approach while keeping constant-delay enumeration
2. Understanding the update time - enumeration delay **trade-off** space
   - Eager and lazy approaches are extremes in this space

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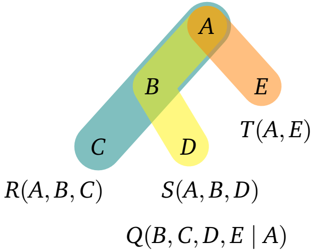
   - More succinct than the listing representation of the query result
   - Less time to compute and maintain
3. The factorized representations support
   - Access requests with any values over the input variables
   - Constant-delay enumeration

Example 1

Consider the query $Q(B, C, D, E \mid A) = R(A, B, C), S(A, B, D), T(A, E)$



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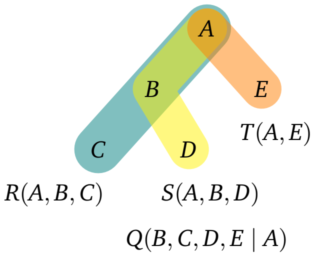

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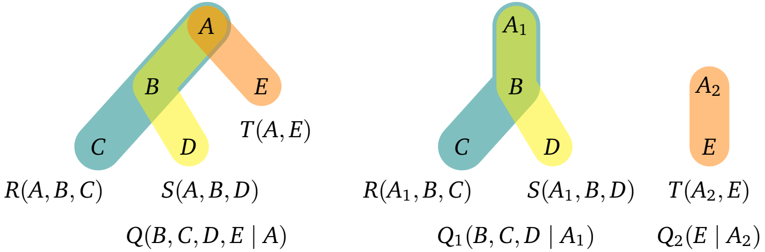

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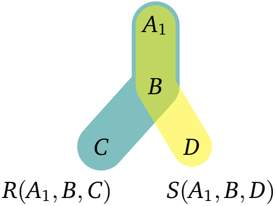

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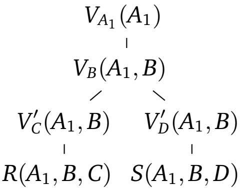

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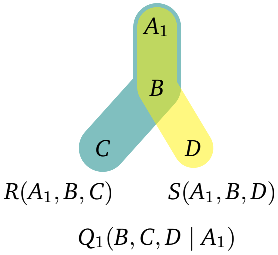

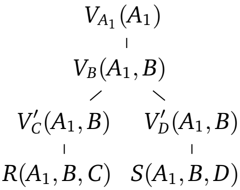

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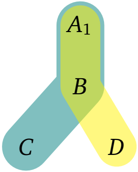

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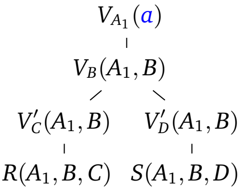

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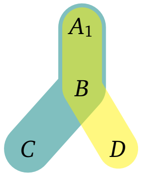

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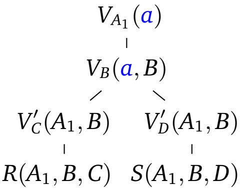

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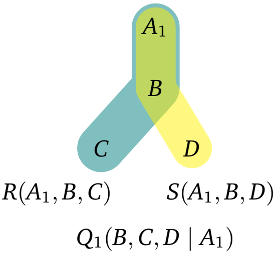

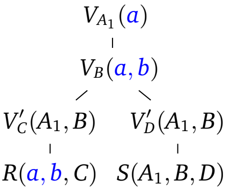

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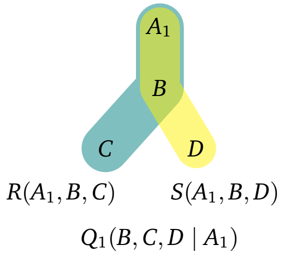

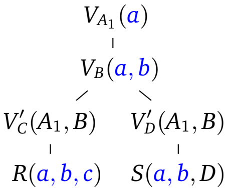

Given an input A_1-value a

check whether $a \in V_{A_1}(A)$

for each $b \in V_B(a, B)$

for each $c \in R(a, b, C)$

for each $d \in S(a, b, D)$

	Preprocessing	Delay	Update
Eager	$\mathcal{O}(N^3)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
Eager-Factorized	$\mathcal{O}(N)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

Example 1

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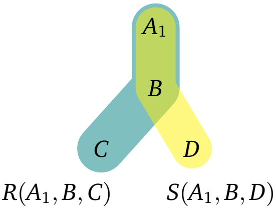
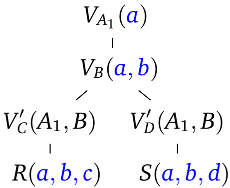


$Q_1(B, C, D \mid A_1)$



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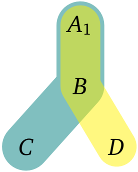
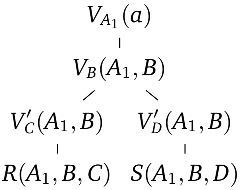


$R(A_1, B, C)$ $S(A_1, B, D)$

$Q_1(B, C, D \mid A_1)$



	Preprocessing	Delay	Update
Eager	$\mathcal{O}(N^3)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
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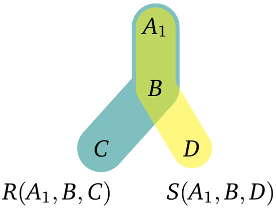
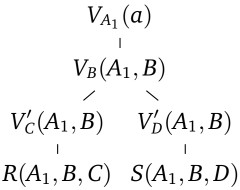


$Q_1(B, C, D \mid A_1)$



Given an update $\delta R(a, b, c)$

	Preprocessing	Delay	Update
Eager	$\mathcal{O}(N^3)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
Eager-Factorized	$\mathcal{O}(N)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

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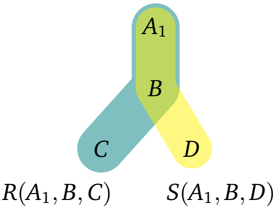
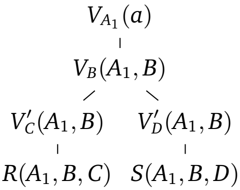
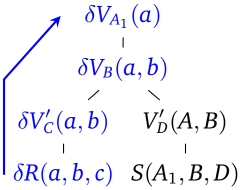


$Q_1(B, C, D \mid A_1)$



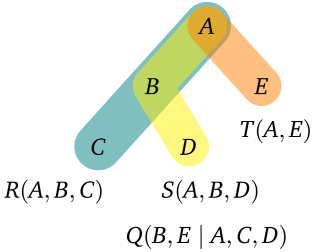


Given an update $\delta R(a, b, c)$

	Preprocessing	Delay	Update
Eager	$\mathcal{O}(N^3)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
Eager-Factorized	$\mathcal{O}(N)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

Example 2

Consider the query $Q(B, E \mid A, C, D) = R(A, B, C), S(A, B, D), T(A, E)$



	Preprocessing	Delay	Update
Eager	$\mathcal{O}(N^3)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
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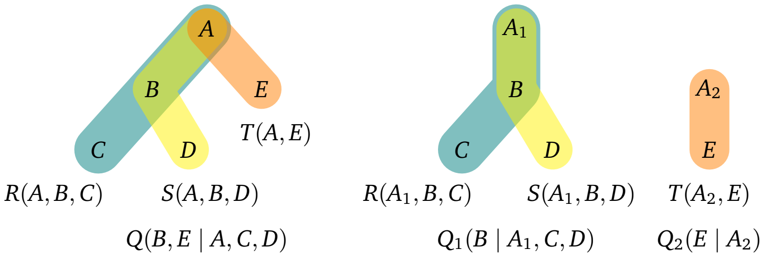

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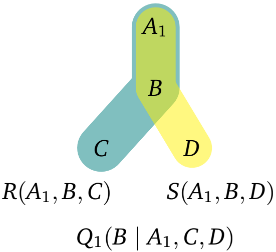

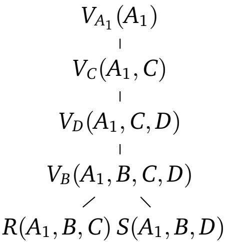

	Preprocessing	Delay	Update
Eager	$\mathcal{O}(N^3)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
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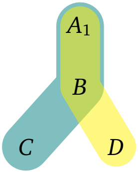

$R(A_1, B, C)$ $S(A_1, B, D)$

$Q_1(B \mid A_1, C, D)$

$V_{A_1}(a)$

$V_C(a, c)$

$V_D(a, c, d)$

$V_B(a, c, d, B)$

$R(A_1, B, C)$ $S(A_1, B, D)$

Given an input tuple (a, c, d) over (A_1, C, D)

	Preprocessing	Delay	Update
Eager	$\mathcal{O}(N^3)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
Eager-Factorized	$\mathcal{O}(N^2)$	$\mathcal{O}(1)$	$\mathcal{O}(N)$

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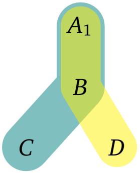
Consider the sub-query $Q_1(B \mid A_1, C, D) = R(A_1, B, C), S(A_1, B, D)$



$R(A_1, B, C)$ $S(A_1, B, D)$

$Q_1(B \mid A_1, C, D)$

$V_{A_1}(a)$

$V_C(a, c)$

$V_D(a, c, d)$

$V_B(a, c, d, B)$

$R(A_1, B, C)$ $S(A_1, B, D)$

Given an input tuple (a, c, d) over (A_1, C, D)

check $(a, c, d) \in V_D(A_1, C, D)$

for each $b \in V_B(a, c, d, B)$

output (a,b,c,d)

	Preprocessing	Delay	Update
Eager	$\mathcal{O}(N^3)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
Eager-Factorized	$\mathcal{O}(N^2)$	$\mathcal{O}(1)$	$\mathcal{O}(N)$

Example 2

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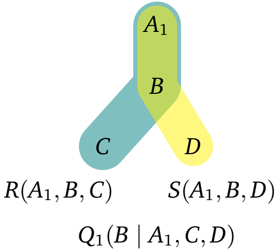

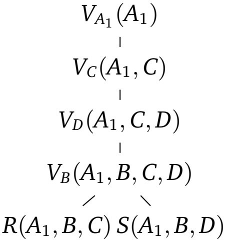

	Preprocessing	Delay	Update
Eager	$\mathcal{O}(N^3)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
Eager-Factorized	$\mathcal{O}(N^2)$	$\mathcal{O}(1)$	$\mathcal{O}(N)$

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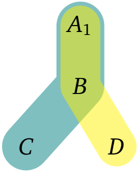
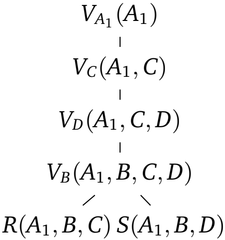


$R(A_1, B, C)$ $S(A_1, B, D)$

$Q_1(B \mid A_1, C, D)$

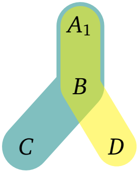


Given an update $\delta R(a, b, c)$

	Preprocessing	Delay	Update
Eager	$\mathcal{O}(N^3)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
Eager-Factorized	$\mathcal{O}(N^2)$	$\mathcal{O}(1)$	$\mathcal{O}(N)$

Example 2

Consider the sub-query $Q_1(B \mid A_1, C, D) = R(A_1, B, C), S(A_1, B, D)$



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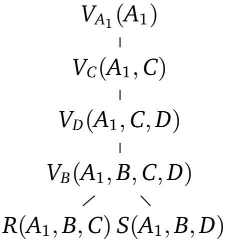
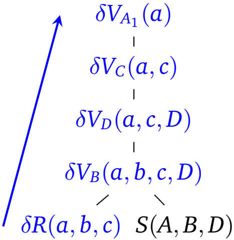




Given an update $\delta R(a, b, c)$

	Preprocessing	Delay	Update
Eager	$\mathcal{O}(N^3)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
Eager-Factorized	$\mathcal{O}(N^2)$	$\mathcal{O}(1)$	$\mathcal{O}(N)$

Different Access Patterns Result in Different Costs

Consider the query $Q(\mathcal{O} \mid \mathcal{I}) = R(A,B,C), S(A,B,D), T(A,E)$. The table shows the evaluation costs of our approach for different access patterns.

$\mathcal{O}$	$\mathcal{I}$	Preprocessing	Delay	Update
$\{A,B,C,D,E\}$	$\{\,\}$	$\mathcal{O}(N)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\{\,\}$	$\{A,B,C,D,E\}$	$\mathcal{O}(N)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\{A,C,D,E\}$	$\{B\}$	$\mathcal{O}(N)$	$\mathcal{O}(1)$	$\mathcal{O}(N)$
$\{A,C,D\}$	$\{B,E\}$	$\mathcal{O}(N^2)$	$\mathcal{O}(1)$	$\mathcal{O}(N)$
$\{A,E\}$	$\{B,C,D\}$	$\mathcal{O}(N^2)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
$\{A,B\}$	$\{C,D,E\}$	$\mathcal{O}(N^3)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
...	...	...	...	...

	Preprocessing	Delay	Update
Eager	$\mathcal{O}(N^3)$	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$

Summary of Contribution 1

- A dynamic evaluation approach for arbitrary CQAPs
- For a CQAP with *static width* w and *dynamic width* δ, our approach admits
  - Preprocessing: $\mathcal{O}(N^{\mathsf{w}})$
  - Update: $\mathcal{O}(N^{\delta})$
  - Enumeration delay: $\mathcal{O}(1)$
- Static width: $s^{\uparrow}$[OZ15] or faqw[AKNR16] specialized to the access pattern
- Dynamic width: maximal static width over all delta queries

Dichotomy Result

$CQAP_0$: static width $\mathsf{w} = 1$ and dynamic width $\delta = 0$

Consider a CQAP query Q and a database of size N.

- If Q is in $CQAP_0$, then it admits $\mathcal{O}(N)$ preprocessing time, $\mathcal{O}(1)$ enumeration delay, and $\mathcal{O}(1)$ update time for single-tuple updates.
- If Q is not in $CQAP_0$ and has no repeating relation symbols, then there is no algorithm that computes Q with arbitrary preprocessing time, $\mathcal{O}(N^{\frac{1}{2}-\gamma})$ enumeration delay, and $\mathcal{O}(N^{\frac{1}{2}-\gamma})$ amortized update time, for any $\gamma > 0$, unless the OMv conjecture fails.

Contribution 2: Trade-Offs in Dynamic Query Evaluation

The eager (listing or factorized) and lazy approaches are the two extremes.

Eager	Lazy
Constant enumeration delay	**High** enumeration delay
High update time	**Constant** update time

Contribution 2: Trade-Offs in Dynamic Query Evaluation

The eager (listing or factorized) and lazy approaches are the two extremes.

Eager

Lazy

Constant enumeration delay

High update time

Performs well when **updates** are less frequent than **access requests**

High enumeration delay

Constant update time

Performs well when **access requests** are less frequent than **updates**

Contribution 2: Trade-Offs in Dynamic Query Evaluation

The eager (listing or factorized) and lazy approaches are the two extremes.

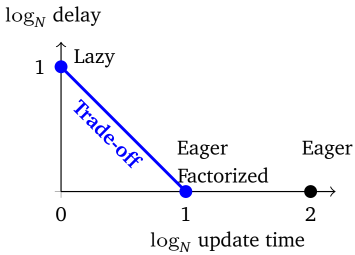
Eager	Ours	Lazy
Constant enumeration delay **High** update time	Trade-offs ⟷	**High** enumeration delay **Constant** update time
Performs well when **updates** are less frequent than **access requests**		Performs well when **access requests** are less frequent than **updates**

Contribution 2: Trade-Offs in Dynamic Query Evaluation

Example: Consider query $Q(A, C, D, E \mid B) = R(A, B, C), S(A, B, D), T(A, E)$.

	Delay	Update
Eager	$\mathcal{O}(1)$	$\mathcal{O}(N^2)$
Eager-Factorized	$\mathcal{O}(1)$	$\mathcal{O}(N)$
Lazy	$\mathcal{O}(N)$	$\mathcal{O}(1)$
Trade-off	$\mathcal{O}(N^{1-\epsilon})$	$\mathcal{O}(N^{\epsilon})$

Evaluation costs of different approaches; $\epsilon \in [0, 1]$



Contribution 2: Trade-Offs in Dynamic Query Evaluation

Trade-offs between preprocessing time, enumeration delay and update time

For **a CQAP with a hierarchical fracture** with

- Static width w
- Dynamic width δ (δ can be w or w $-$ 1)

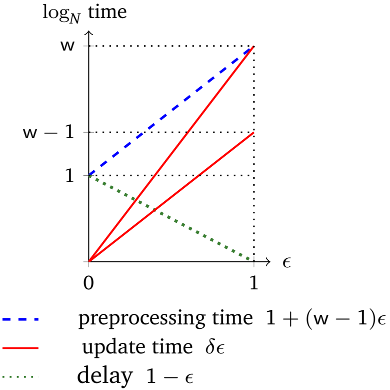
Optimality results for the CQAPs with hierarchical fractures

- Strongly Pareto optimal:

  $CQAP_0$ (w $= 1$, $\delta = 0$)

- Weakly Pareto optimal:

  $CQAP_1$ (w $= 1$, $\delta = 1$)



Summary

Fully dynamic evaluation for CQAPs

1. A dynamic evaluation approach for arbitrary CQAPs
2. A dichotomy result in the evaluation of CQAPs
3. Evaluation trade-offs for CQAPs

References I

[AKNR16] Mahmoud Abo Khamis, Hung Q. Ngo, and Atri Rudra. FAQ: Questions Asked Frequently. In *PODS*, pages 13–28, 2016.

[OZ15] Dan Olteanu and Jakub Závodný. Size Bounds for Factorised Representations of Query Results. *ACM TODS*, 40(1):2:1–2:44, 2015.

Appendix: Query Fracture

Consider the triangle query

$$Q(B, C \mid A) = R(A, B), S(B, C), T(A, C).$$

By replacing A with A_1 and A_2, we get

$$Q'(B, C \mid A_1, A_2) = R(A_1, B), S(B, C), T(C, A_2).$$

The static width increases from $\mathsf{w}(Q) = 1.5$ to $\mathsf{w}(Q') = 2$.

Appendix: Query Fracture

Consider the 4-cycle query

$$Q(B, D|A, C) = R(A, B), S(B, C), T(C, D), U(A, D).$$