TreeToaster: Enabling Declarative Compilers

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Johannes Luong[*], Hinnerk Gildhoff[*], Gaurav Saxena[*]

Amazon[*], *University At Buffalo*[†]

Dec 12, 2024

Compilers

```
SELECT A, C
FROM R, S
WHERE C >= 3 AND R.B = S.B
```

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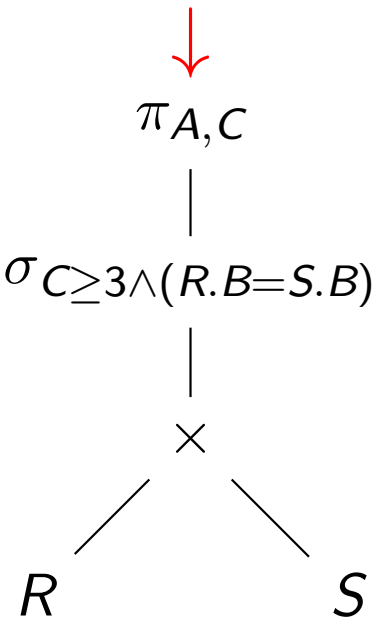
Parsing



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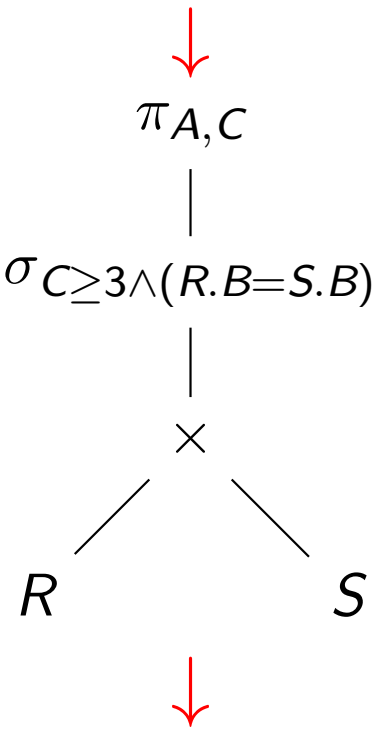
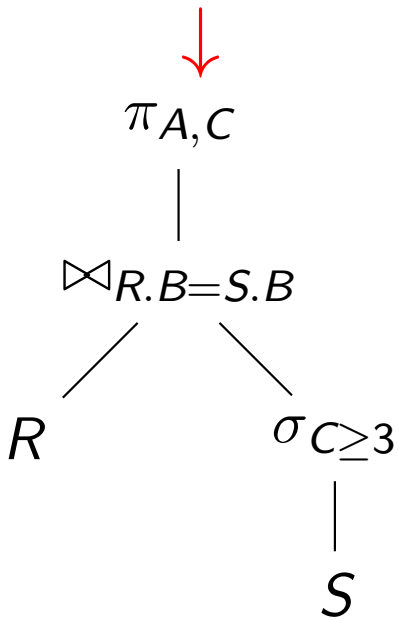


Optimization



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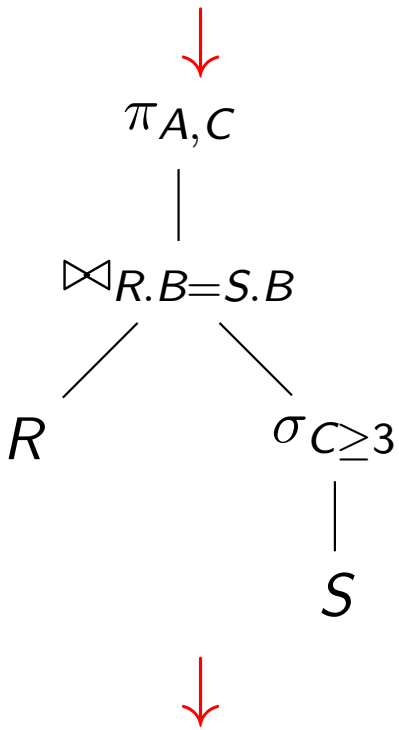


Translation

```
data = {}
for r in R:
  data[r.B] = r
for s in S:
  if s.C >= 3:
    r = data[s.B]
    print(r.A, s.C)
```

Translation

```
data = {}
for r in R:
  data[r.B] = r
for s in S:
  if s.C >= 3:
    r = data[s.B]
    print(r.A, s.C)
```

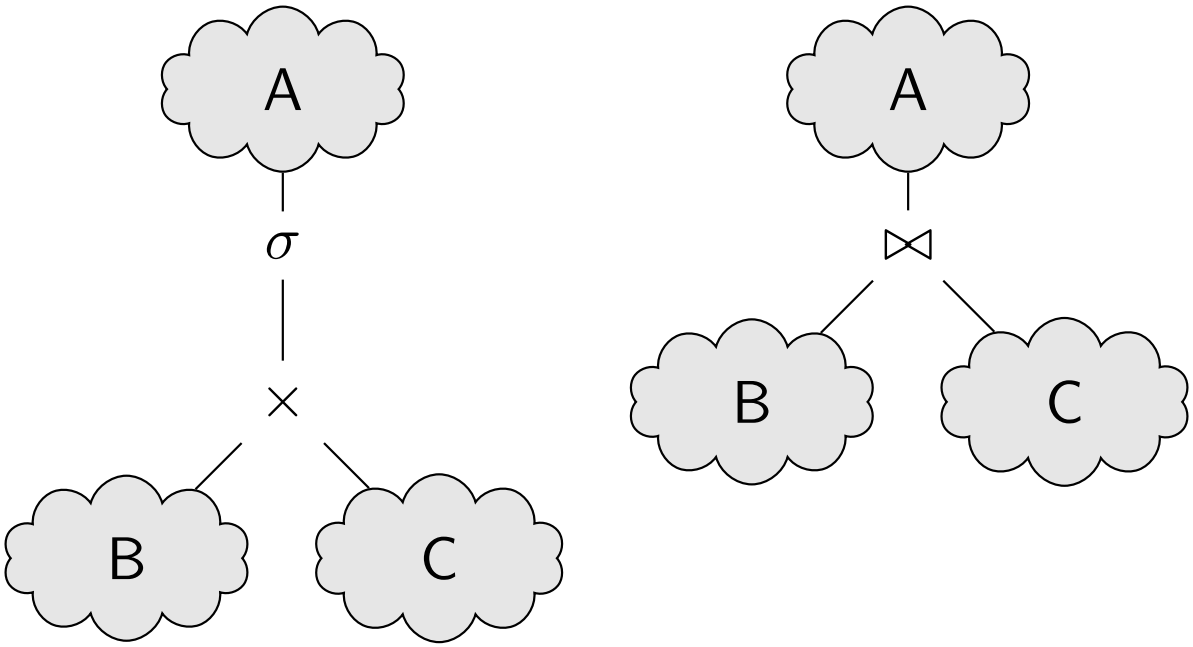
Analysis

```
data = {}
for r in R:                 # 10^6 rows
  data[r.B] = r
for s in S:                 # 10 rows
  if s.C >= 3:              # 50% selectivity
    r = data[s.B]           # 100% selectivity
    print(r.A, s.C)
```

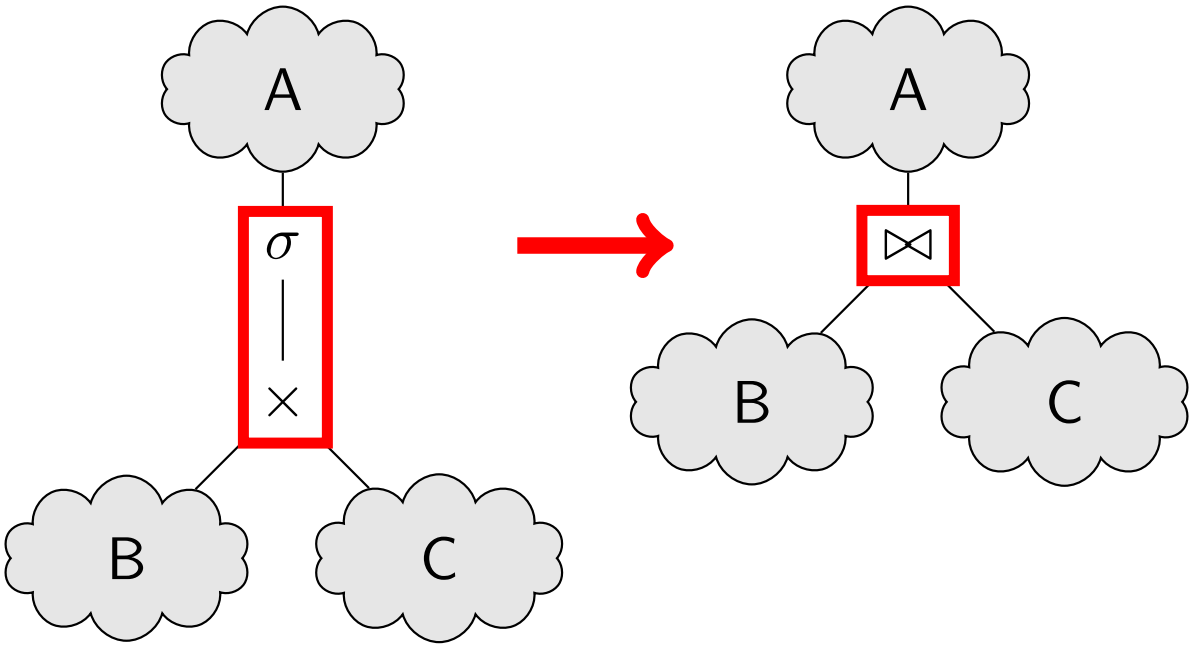
Match/Case Expressions

```
Q = Q match {
  case Filter(Equals(A, B), Cross(R, S))
    if A in R.sch && B in S.sch =>
      Join(R, S, A, B)
  case x => x
}
```

Local Reasoning



Local Reasoning



Optimization

$$\texttt{rule}_1(Q) \rightarrow \text{better} Q$$

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$$\texttt{rule}_2(\text{better}Q) \rightarrow \text{better}^2 Q$$

$$\texttt{rule}_3(\text{better}^2 Q) \rightarrow \text{better}^3 Q$$

$$\ldots$$

Optimization

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$$\texttt{rule}_1(\text{better}^N Q) \rightarrow \text{better}^{N+1} Q$$

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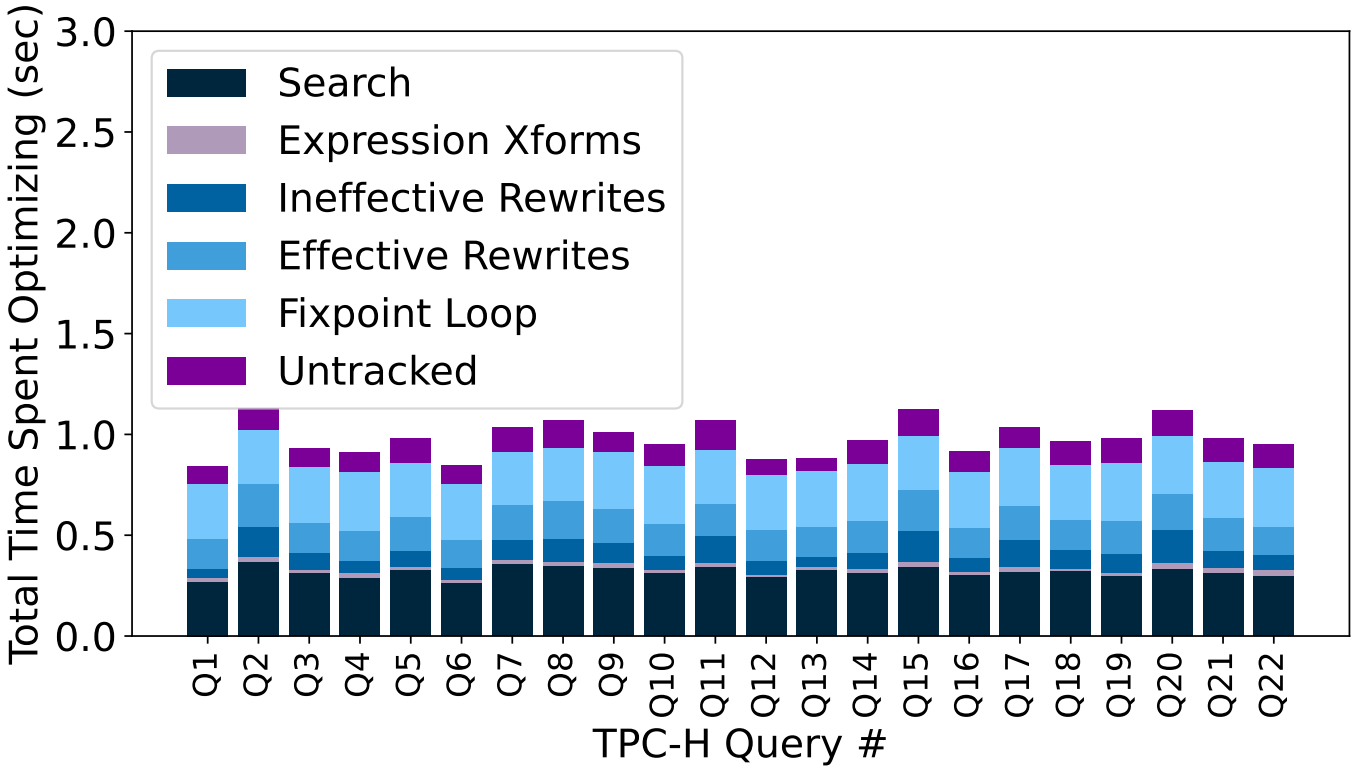
$$\texttt{rule}_2(\text{better}^{N+1} Q) \rightarrow \text{better}^{N+2} Q$$

$$\ldots$$

Fixed Point Loops

```
while AST is being changed:
  for rule in rules:
    for node in AST:
      if rule matches node:
        replace node with rule(node)
```

Apache Spark / Catalyst



Fixed Point Loops

```
while AST is being changed:
  for rule in rules:
    for node in AST:
      if rule matches node:
        /* ... */
```

The Fixed Point Loop Abstraction

Pro

- Simple
- Easy to Reason About

Con

- Slow
- Limited Expressiveness

A Broader Perspective

We've been talking about queries...

...but the same ideas show up in compilers in general.

Compilers are Databases

```
case Filter(Equals(A, B), Cross(R, S)) if ... =>
  Join(R, S, A, B)
```

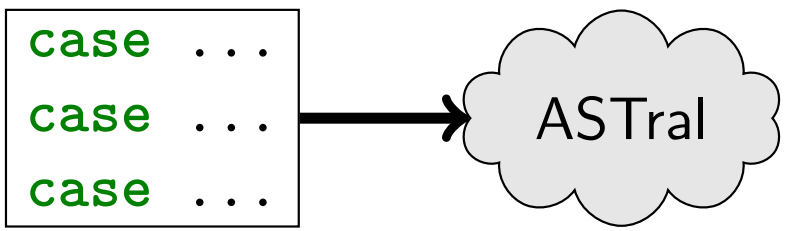
vs

```
UPDATE ast SET node = Join(R, S, A, B)
   WHERE node LIKE Filter(Equals(A, B), ....
```

The ASTral Compiler

```
case ...
case ...
case ...
```

The ASTral Compiler



The ASTral Compiler

Overview

- Optimization Rules as Queries
- Evaluating ASTral
- Indexing & Incremental View Maintenance
- State Machines for Multiquery Optimization

Optimization Rules as Queries

Breaking down a Pattern

```
case Filter(Equals(A, B), Cross(R,S))

        if A in R.sch && B in S.sch => ...
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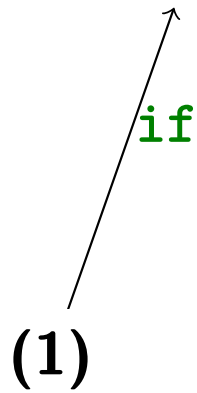
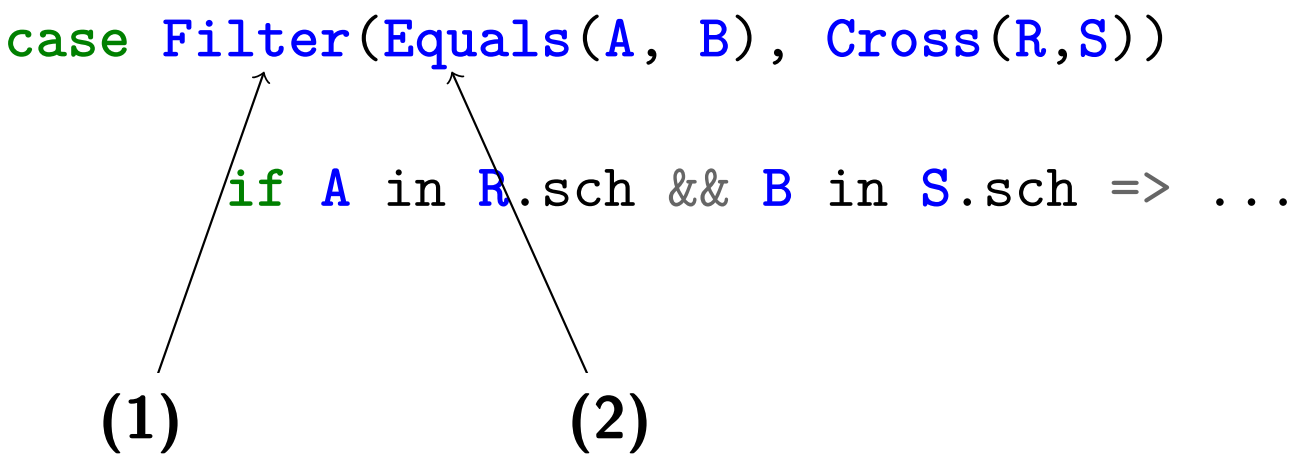


Breaking down a Pattern



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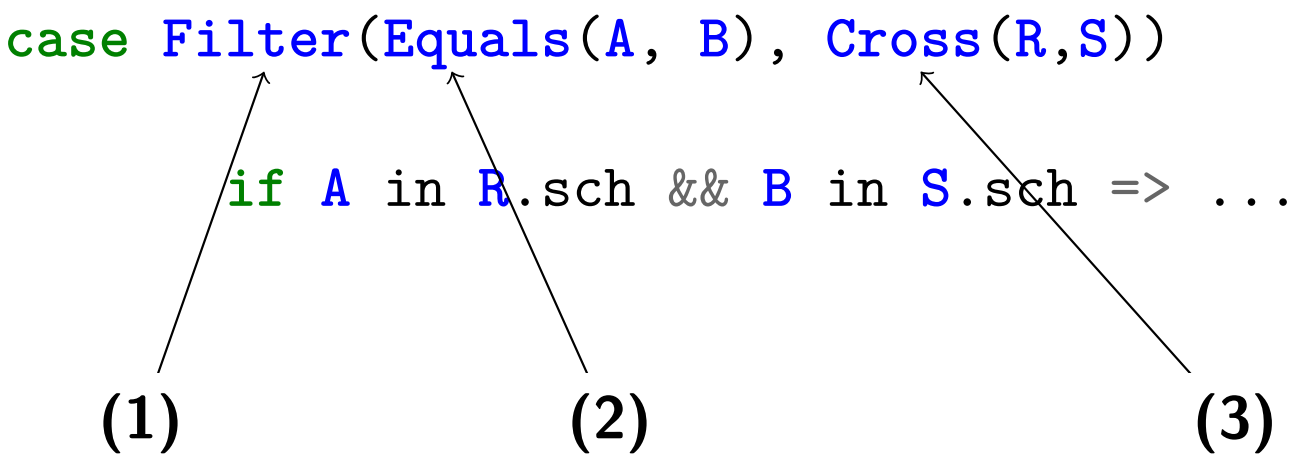

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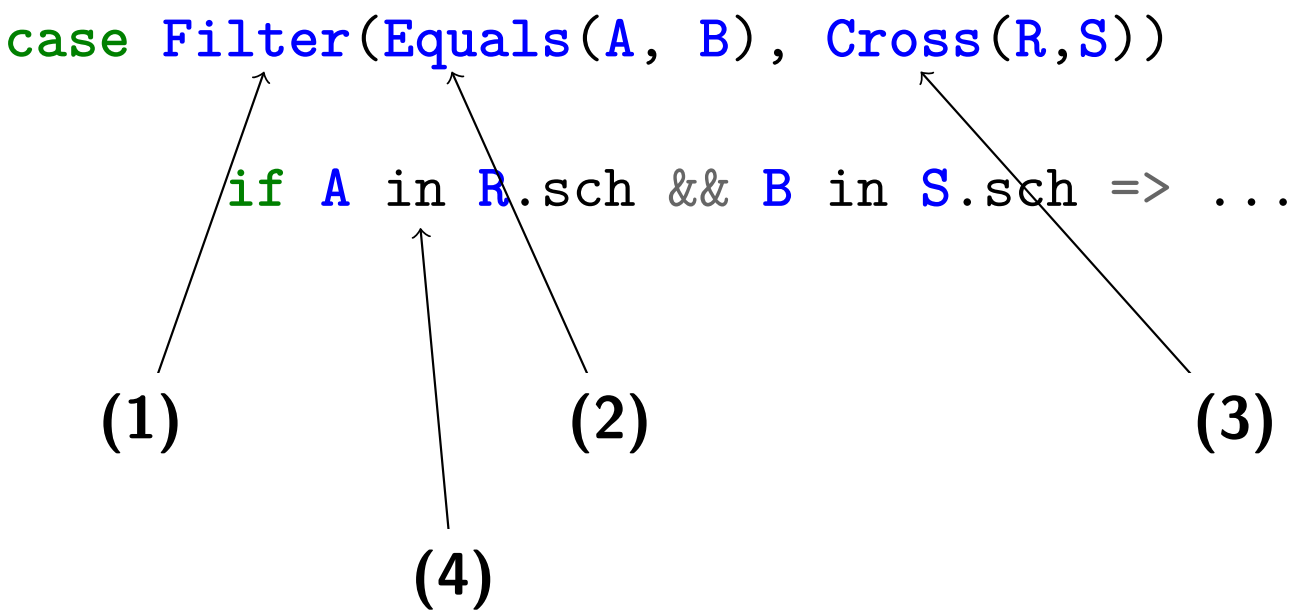
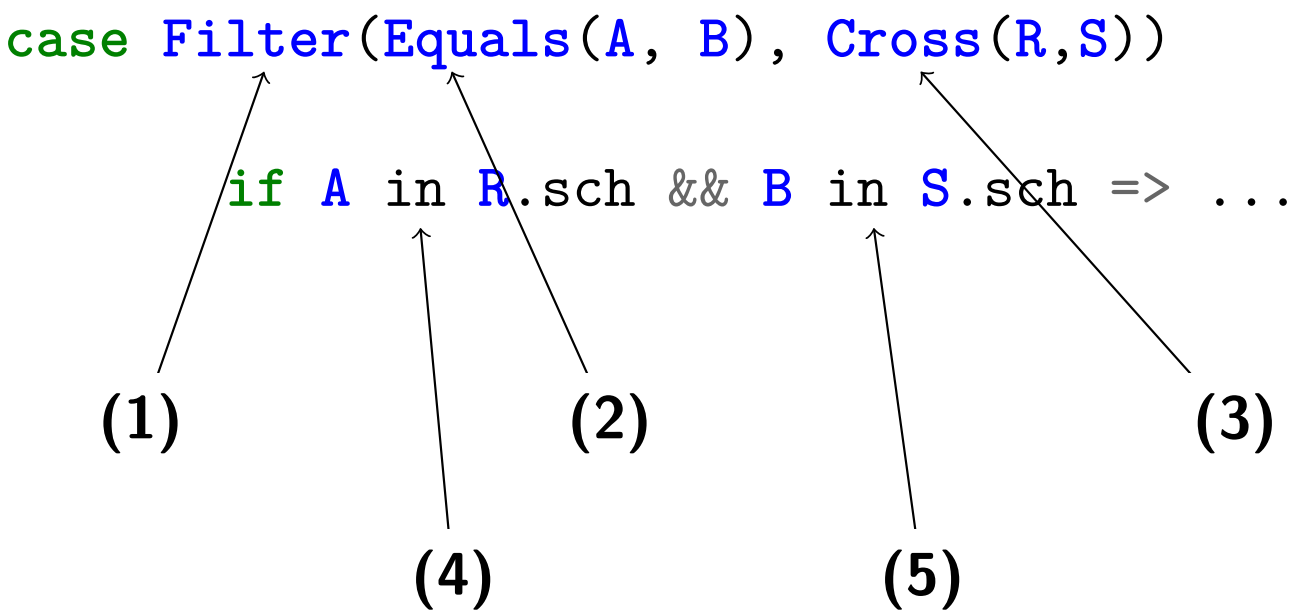


Breaking down a Pattern



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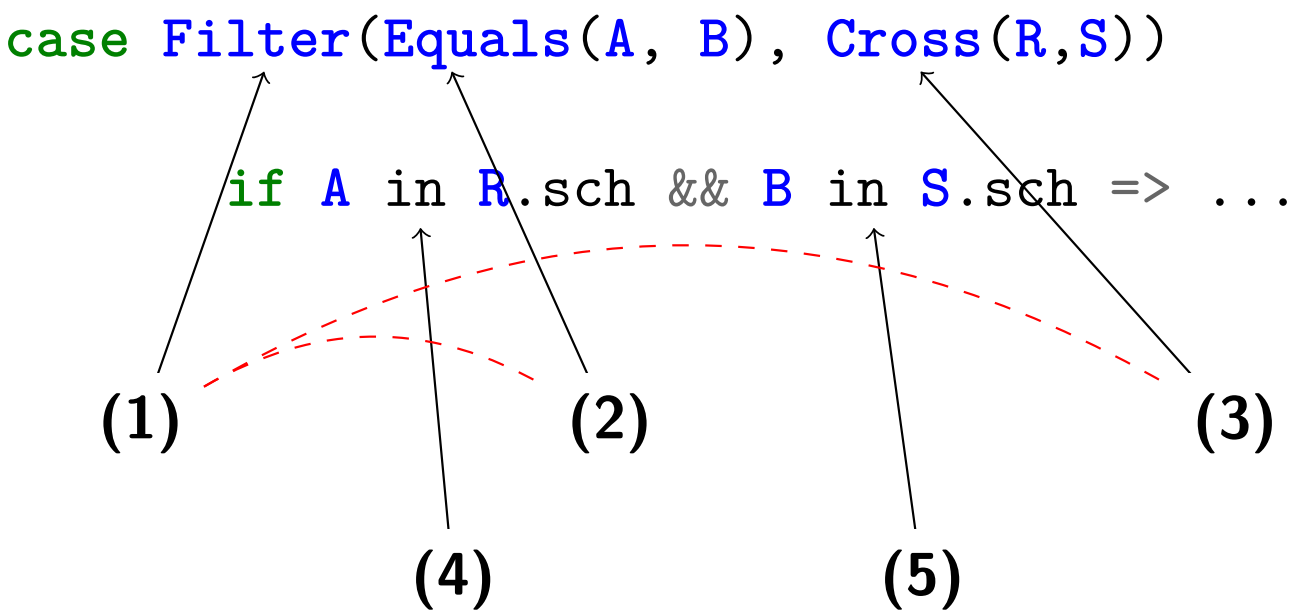

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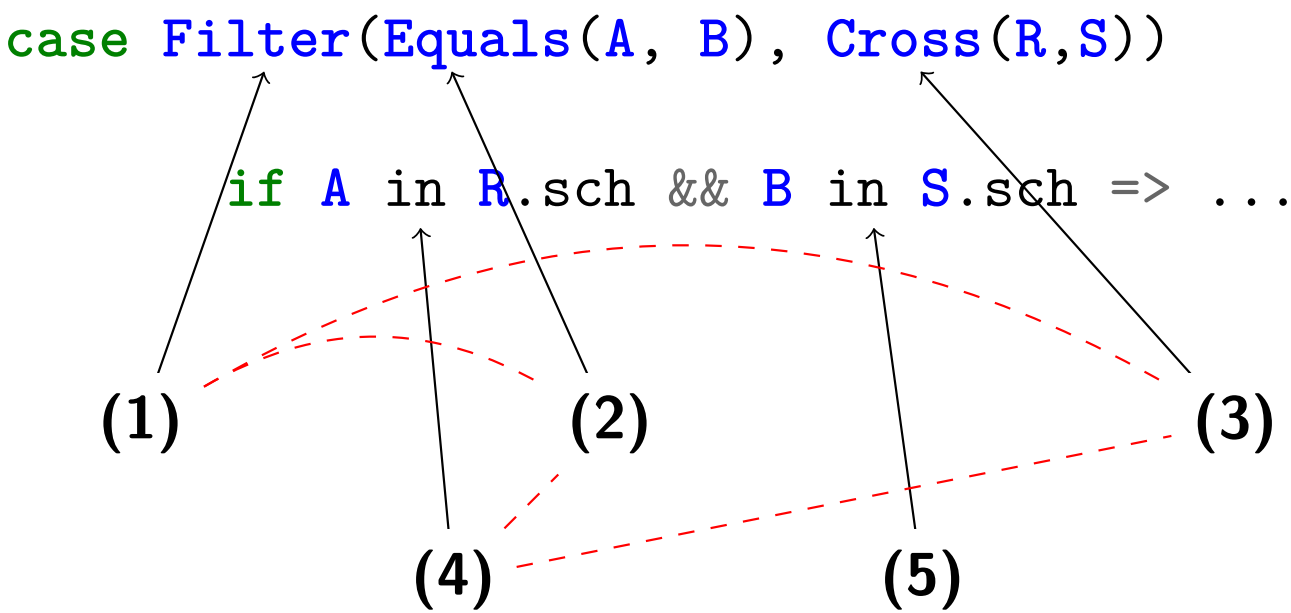

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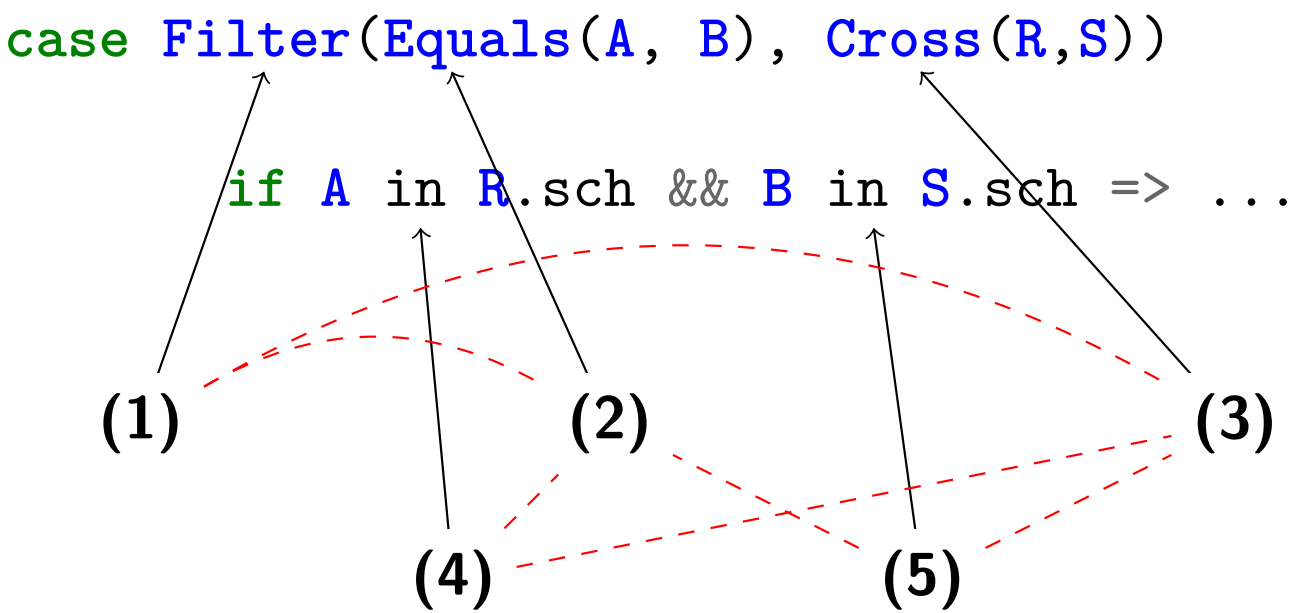


ASTral (The AST-Relational Algebra)

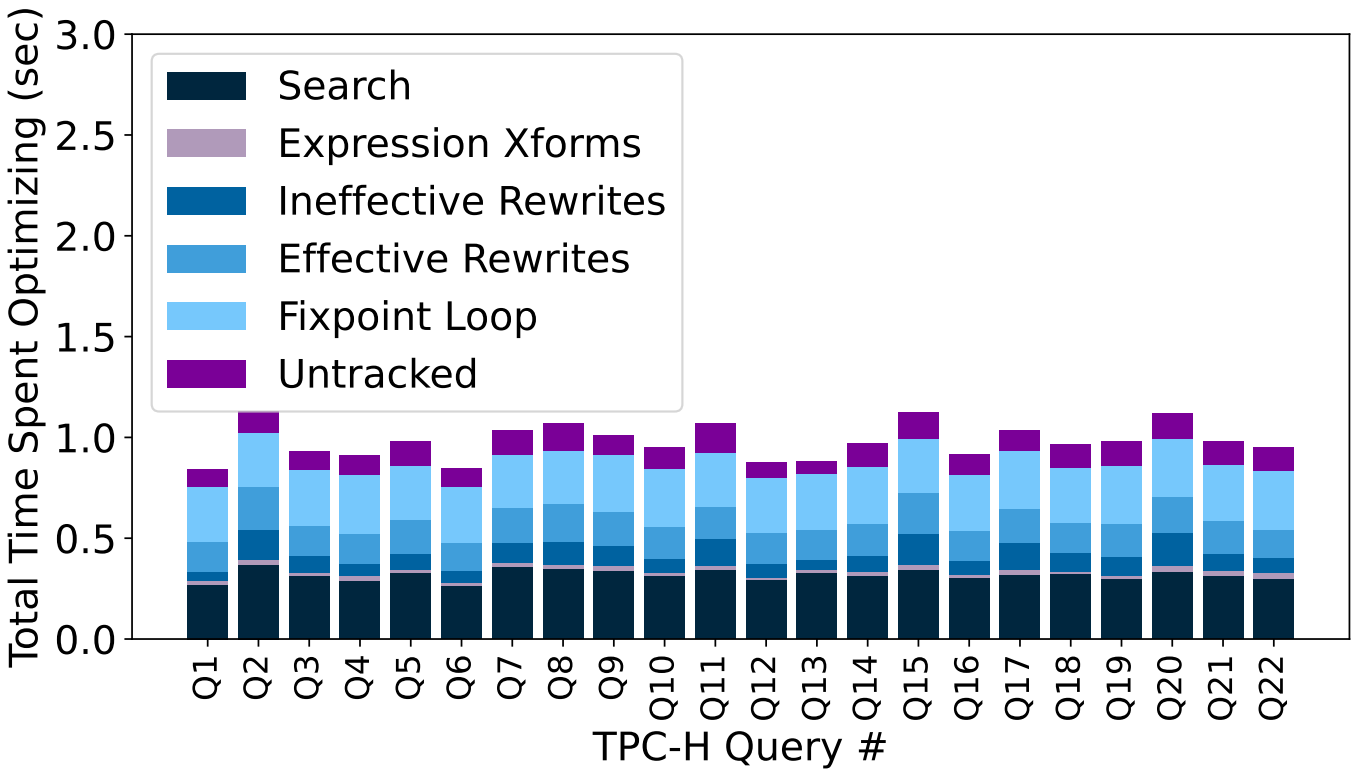
1. $\mathbf{Node} \sim \texttt{Filter}(\mathbf{X}, \mathbf{Y})$
2. $\wedge\ \mathbf{X} \sim \texttt{Equals}(\mathbf{A}, \mathbf{B})$
3. $\wedge\ \mathbf{Y} \sim \texttt{Cross}(\mathbf{R}, \mathbf{S})$
4. $\wedge\ \mathbf{A} \in \mathbf{R}.\texttt{sch}$
5. $\wedge\ \mathbf{B} \in \mathbf{S}.\texttt{sch}$

Evaluating ASTral

Compiled

```
for X in descendants(ROOT):
  if X is Filter:
    Y = X.condition
    Z = X.child
    if Y is Equality;
      A = Y.lhs
      B = Y.rhs
      if Z is Cross;
        R = Z.lhs
        S = Z.rhs
        if A in R.sch:
          if B in S.sch:
            replace X with Join(A, B, R, S)
```

Optimizer Performance



Performance Opportunities

```
for X in descendants(ROOT):
  if X is Filter:
    Y = X.condition
    Z = X.child
    if Y is Equality;
      A = Y.lhs
      B = Y.rhs
      if Z is Cross;
        R = Z.lhs
        S = Z.rhs
        if A in R.sch:
          if B in S.sch:
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So now what?

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for X in descendants(ROOT):
  if X is Filter:
    ...
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for X in descendants(ROOT):
  if X is Filter:
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```

Build an index on $\mathit{Ancestor}(\mathbf{ROOT}, \mathbf{X}) \wedge \mathbf{X} \sim \texttt{Filter}(\_, \_)$

Indexing

Indexing

```
for X in descendants(ROOT):
  if X is Filter:
    Y = X.condition
    Z = X.child
    ...
```

vs

```
for X in Index:
  Y = X.condition
  Z = X.child
  ...
```

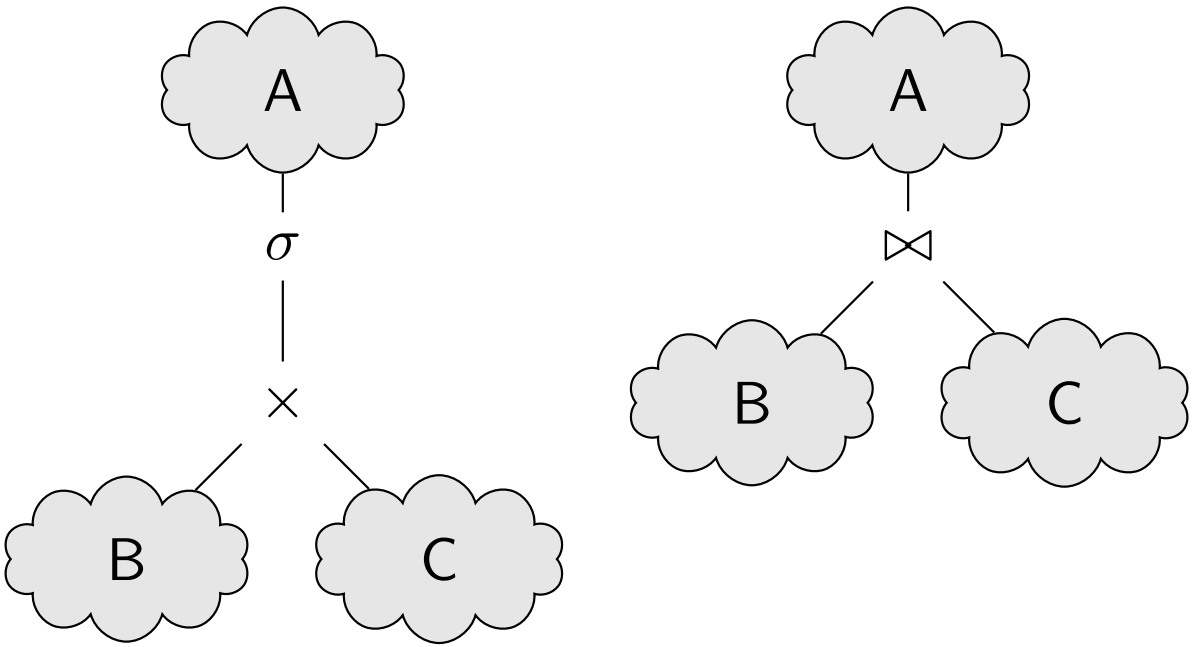
Index Maintenance

$$\mathit{Index}(X) :- \ \mathit{Ancestor}(\mathbf{ROOT}, \mathbf{X}) \wedge \mathbf{X} \sim \texttt{Filter}(\_, \_)$$

Say we replace $\sigma(\times(R, S))$ in the tree with $\bowtie(R, S)$.

How does $\mathit{Index}(X)$ change?

Index Maintenance



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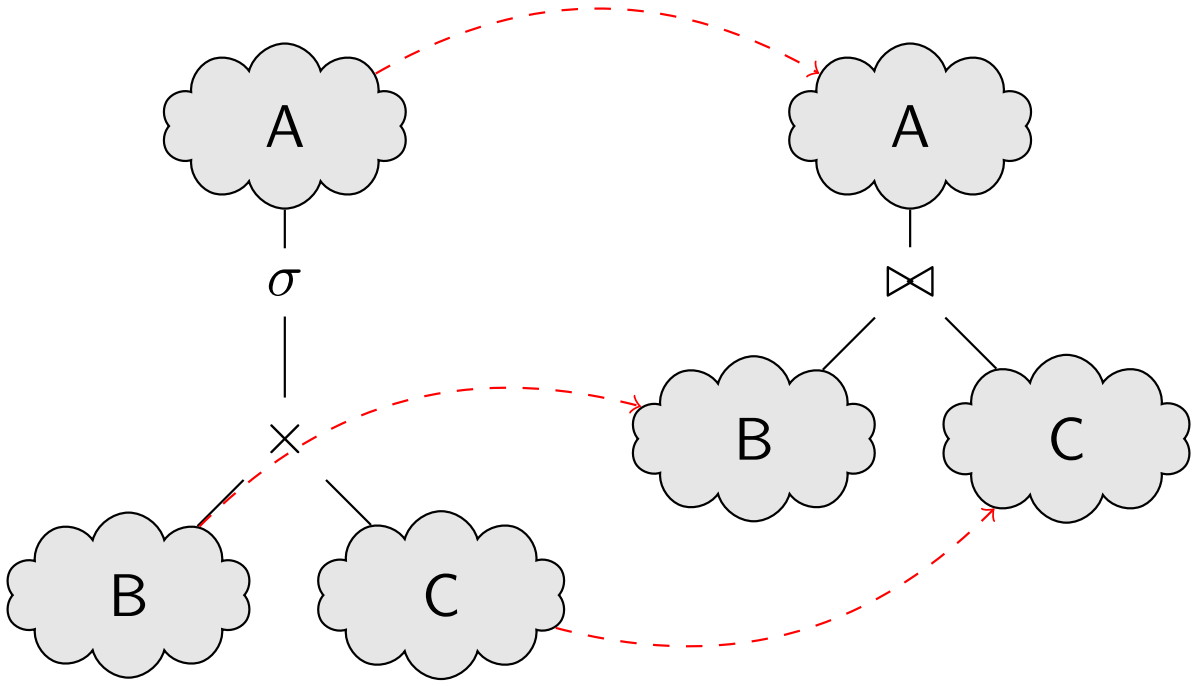

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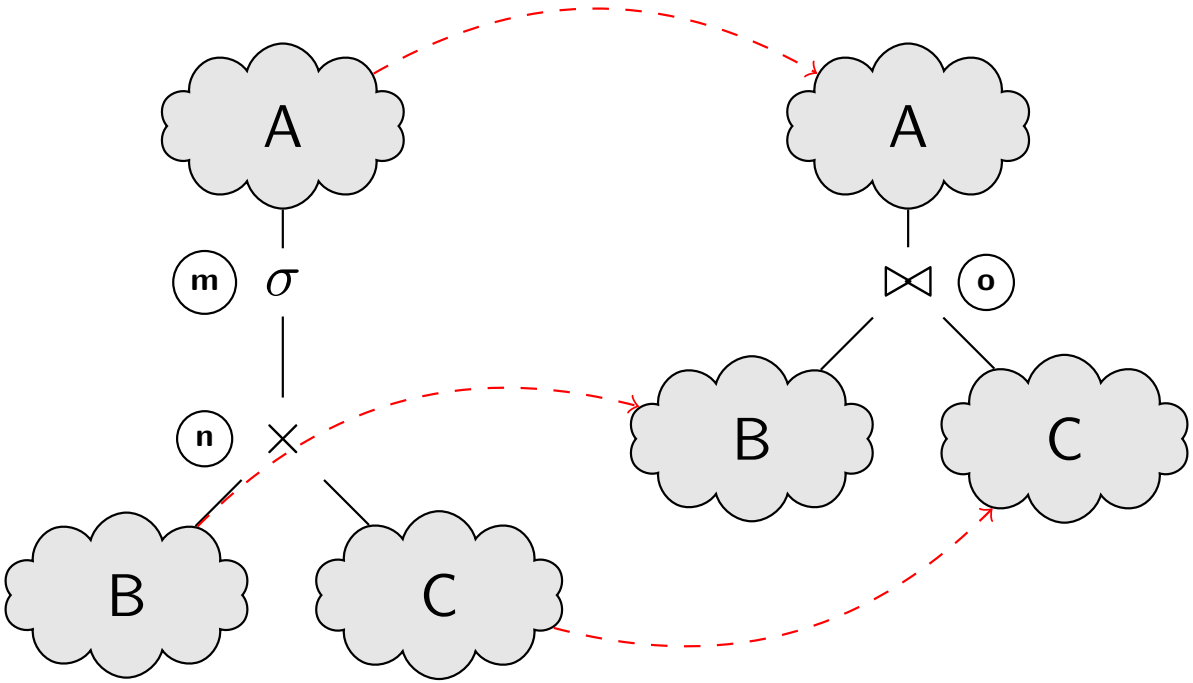

Why stop at indexing?

Why not just compute:

$$
\begin{aligned}
\mathit{Index}_1(X) :- \quad & \mathit{Ancestor}(\mathbf{ROOT}, \mathbf{X}) \\
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& \wedge\ \mathbf{A} \in \mathbf{R}.\texttt{sch} \wedge \mathbf{B} \in \mathbf{S}.\texttt{sch} \\
\mathit{Index}_2(X) :- \quad & \ldots \\
\mathit{Index}_3(X) :- \quad & \ldots
\end{aligned}
$$

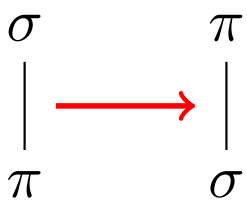
Incremental View Maintenance

Rewrites Under IVM

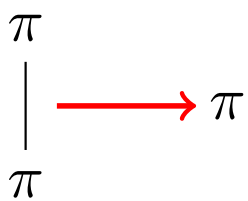
```
while AST is being changed:
  for rule in RULES:
    while Index[rule] is not empty:
      rewrite Index[rule][0] with rule
      update Indexes
```

But...

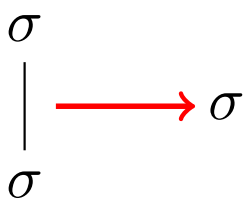
Rule 1



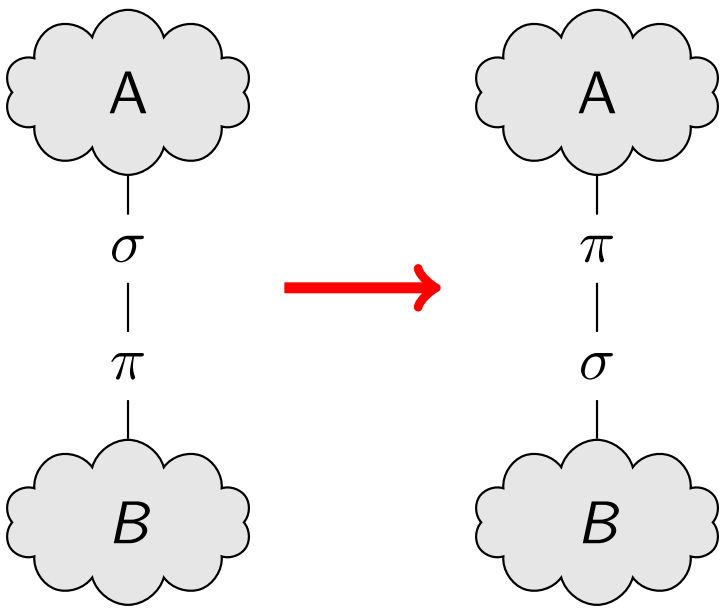
Rule 2



Rule 3



Updating Materialized Views



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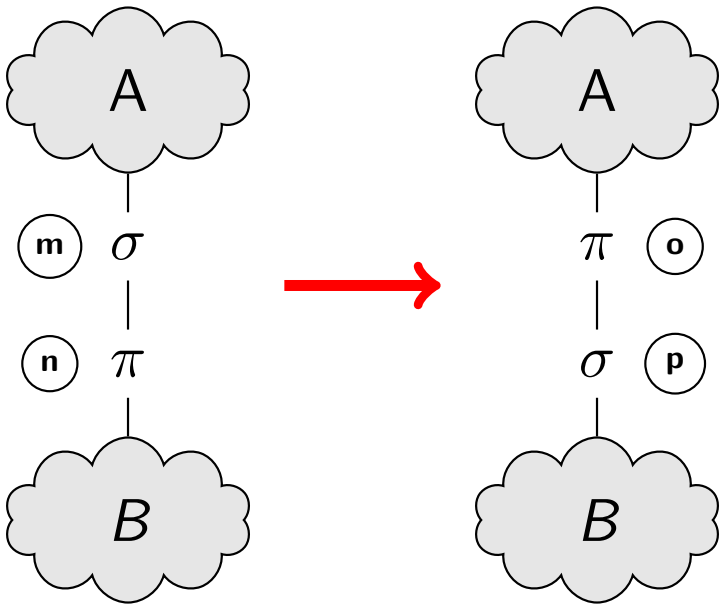

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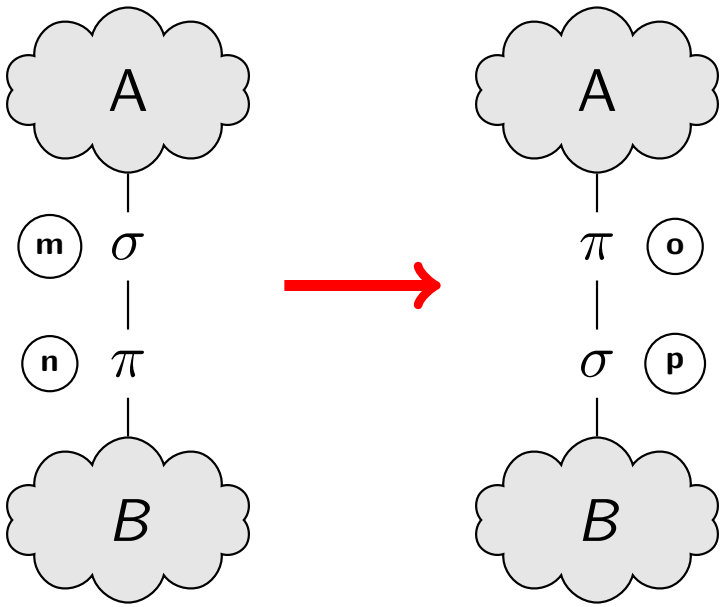
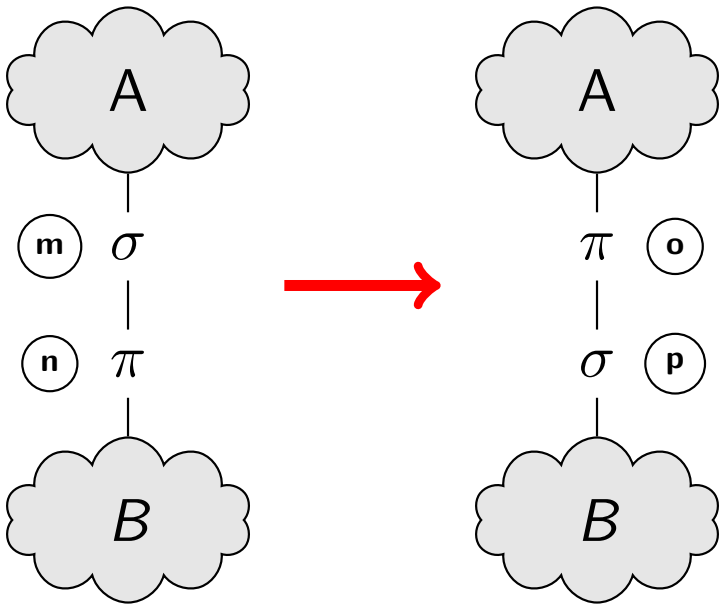


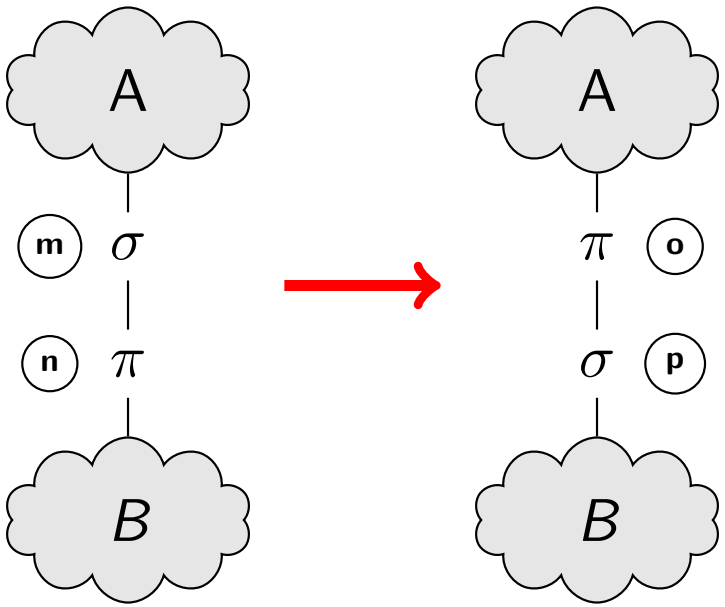
- Remove *n*, *m* from indices.

Updating Materialized Views



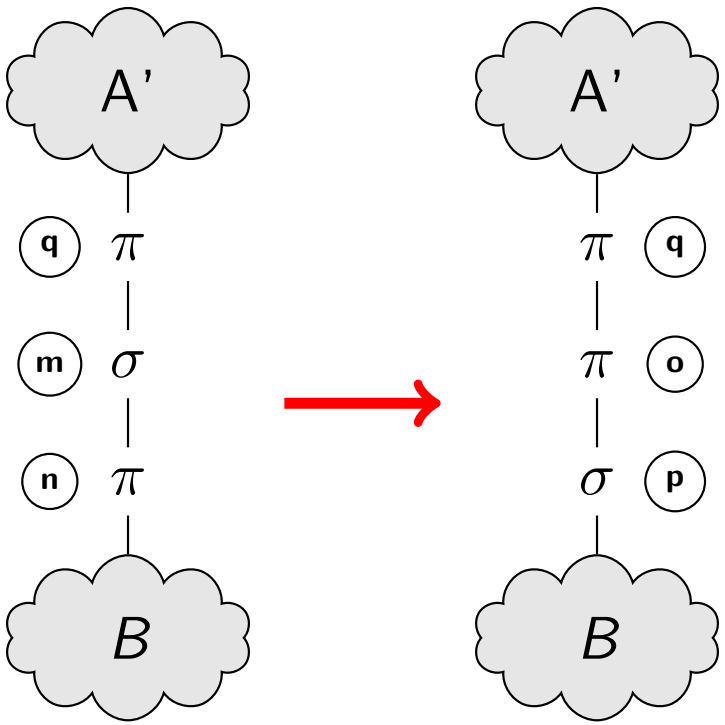
- Remove n, m from indices.
- Check o, p for matches.

Updating Materialized Views



- Remove *n*, *m* from indices.
- Check *o*, *p* for matches.
- Done?

Updating Materialized Views



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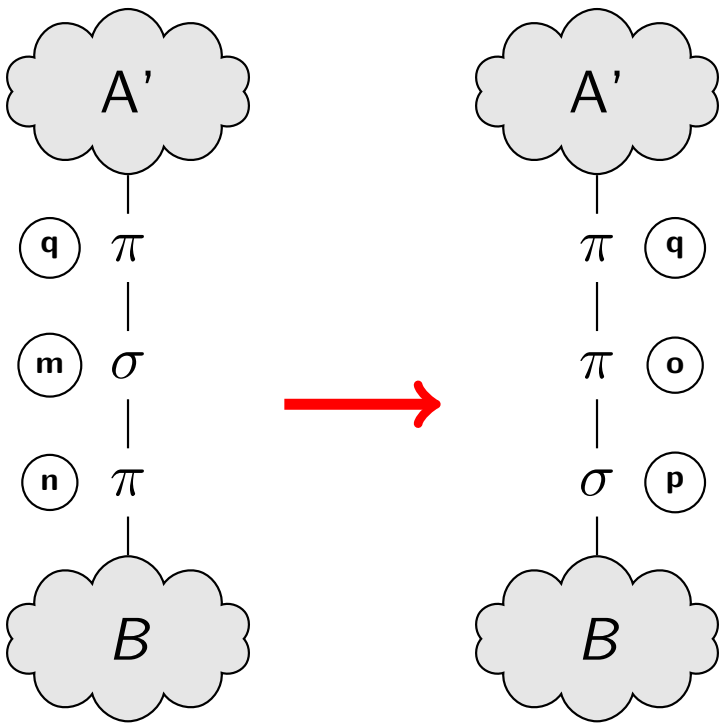
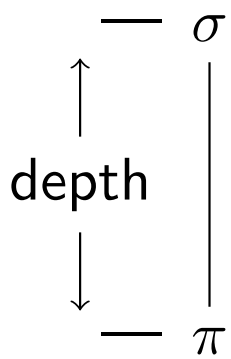


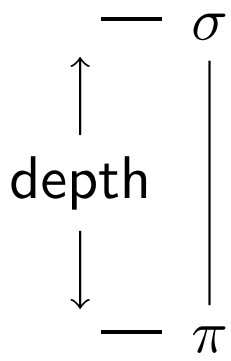
Problem: (q) now matches on Rule 2.

Depth-Bounded Search

Depth-Bounded Search



Depth-Bounded Search



A rule of depth d needs to check d ancestors for a match.

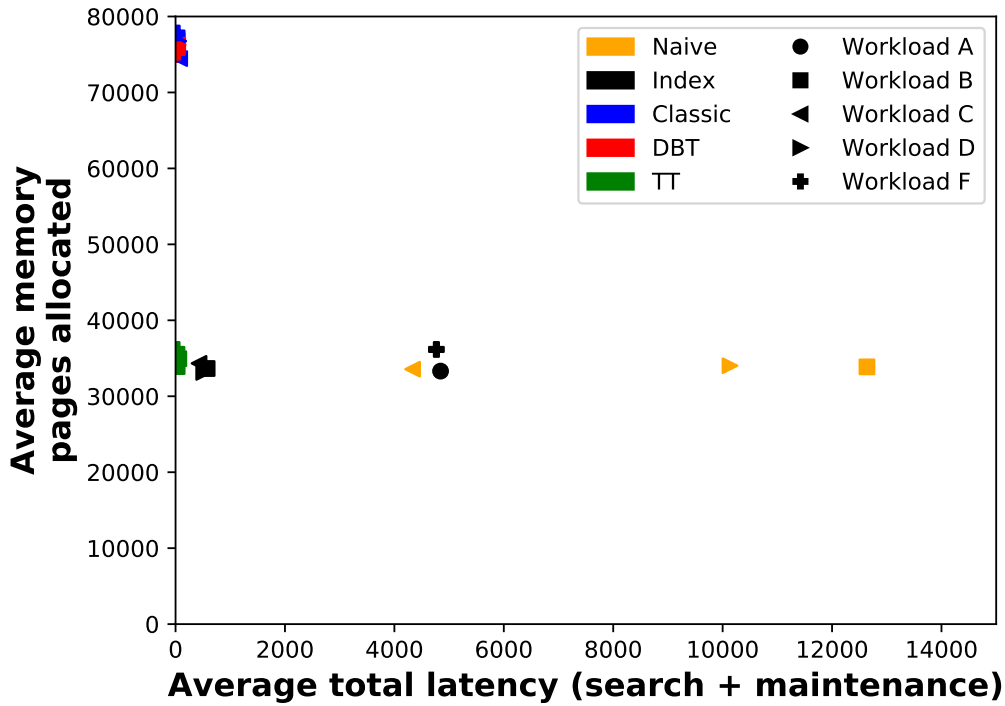
And also...

- In-Situ parallel updates on Trees
- Aggressive Code In-lining

"Fluid Data Structures"; Balakrishnan, Ziarek, Kennedy (DBPL 2019)

"Tree Toaster: Towards an IVM-Optimized Compiler", Balakrishnan et. al. (SIGMOD 2020)

Faster



"Tree Toaster: Towards an IVM-Optimized Compiler", Balakrishnan et. al. (SIGMOD 2020)

State Machines

Back to the fixed point loop...

```
while AST is being changed:
  for rule in rules:
    for node in AST:
      if node matches rule:
        rewrite node
```

Spatial Locality

```
while AST is being changed:
  for node in AST:
    for rule in rules:
      if node matches rule:
        rewrite node
```

Eliminate Redundancy

```
while AST is being changed:
  for node in AST:
    rule = match node in RuleIndex:
    rewrite node
```

De-duplicating Atoms

$$
\begin{aligned}
Q_1(\mathbf{X}) :- \quad & \mathit{Ancestor}(\mathbf{ROOT}, \mathbf{X}) \\
& \wedge\ \mathbf{X} \sim \texttt{Filter}(\mathbf{Y}, \mathbf{Z}) \\
& \wedge\ \mathbf{Y} \sim \texttt{Equals}(\mathbf{A}, \mathbf{B}) \\
& \wedge\ \mathbf{Z} \sim \texttt{Cross}(\mathbf{R}, \mathbf{S}) \\
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Q_2(\mathbf{X}) :- \quad & \mathit{Ancestor}(\mathbf{ROOT}, \mathbf{X}) \\
& \wedge\ \mathbf{X} \sim \texttt{Filter}(\mathbf{Y}, \mathbf{Z}) \\
& \wedge\ \mathbf{Z} \sim \texttt{Project}(\mathbf{P}, \mathbf{S})
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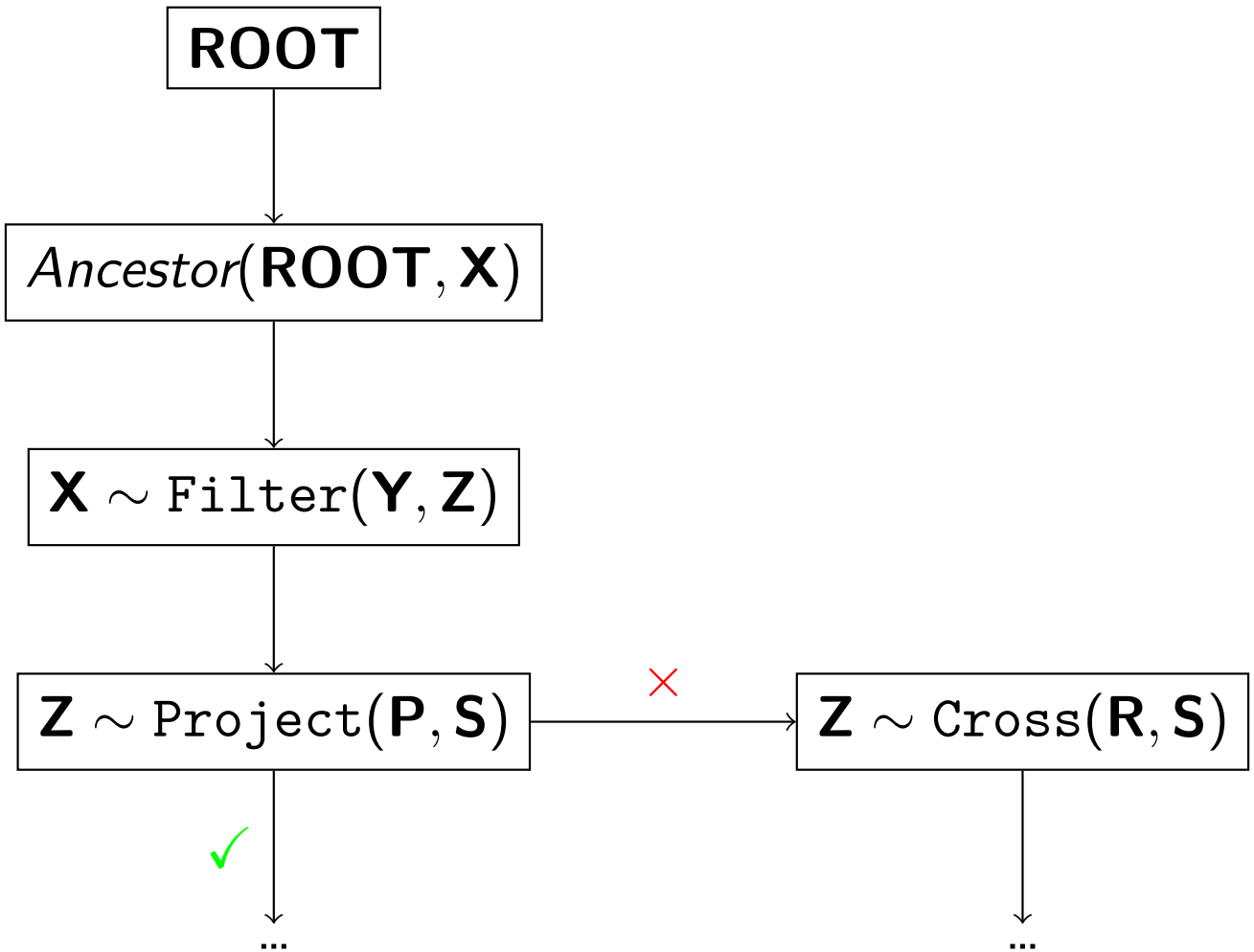
\end{aligned}
$$

Q_1 and Q_2 share a prefix; Only check it once

State Machines



Expensive Predicates

Simple tests (e.g., $\mathbf{X} \sim \texttt{Filter}(\mathbf{Y}, \mathbf{Z})$) are cheap.

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...but some tests (does there exist a descendant with a columnar storage model?) present substantial opportunities for work sharing.

Conclusions

Databases for Compilers

Compilers are an exciting database workload!

The PL Community

- **Equality Saturation: A New Approach to Optimization**
  Tate et. al.
- **Better Together: Unifying Datalog and Equality Saturation**
  Zhang et. al.
- **Soufflé**
  `https://souffle-lang.github.io/`
- **Higher-Order, Data-Parallel Structured Deduction**
  Gilray et. al.

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Conclusions

Revisiting optimization (and translation and analysis) rules as queries creates opportunities for automatic optimization.

Decoupling compiler rewrite logic from performance optimizations makes each easier to reason about.

Find **Nick** to talk about program analysis on disk, and **Victoria** to talk about distributed IVM.
(and **Pratik** to talk about schema management for longitudinal surveys)