Lecture #14

Carnegie Mellon University

ADVANCED DATABASE SYSTEMS

Server-side Logic Execution

Andy Pavlo // 15-721 // Spring 2023

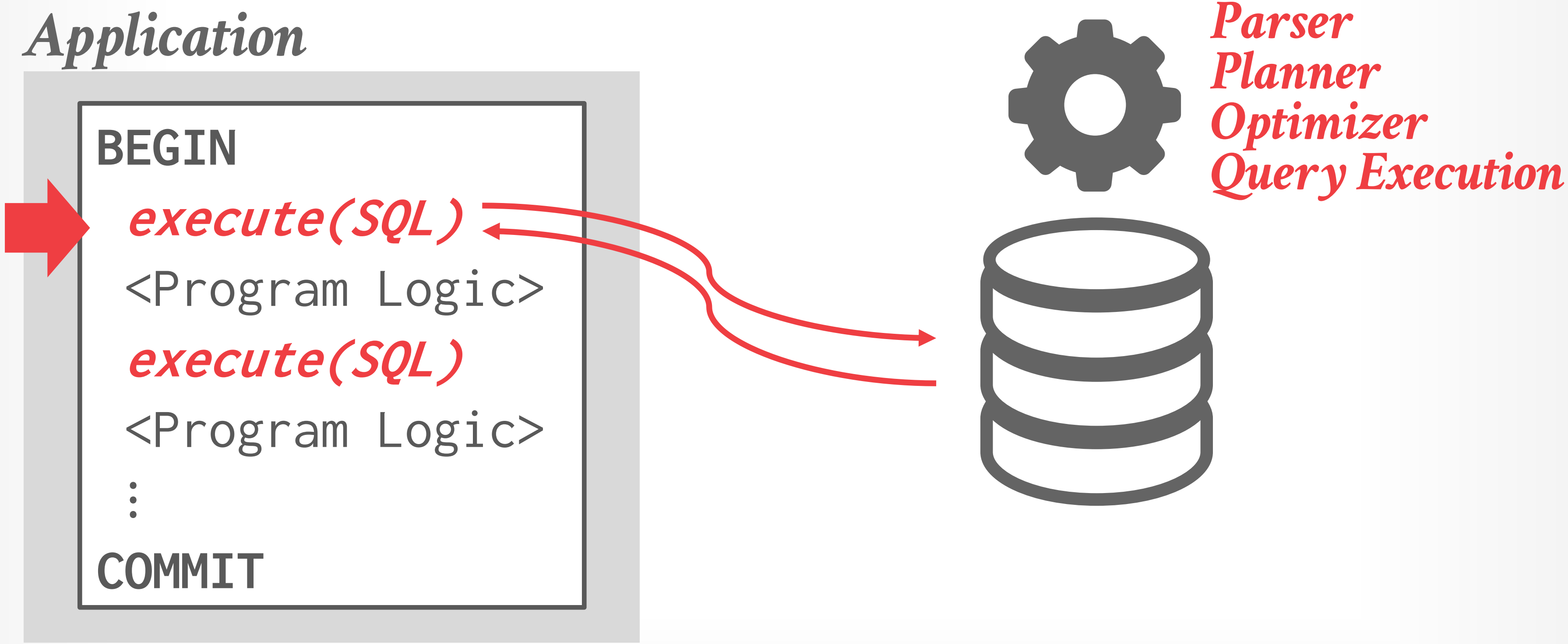
OBSERVATION

Until now, we have assumed that all the logic for an application is in the application.

The application has a "conversation" with the DBMS to store/retrieve data.

- → The application initiates the transfer of data from the DBMS, performs some computation on that data, and then retrieves more data from the DBMS.
- → Protocols: JDBC, ODBC

CONVERSATIONAL DATABASE API

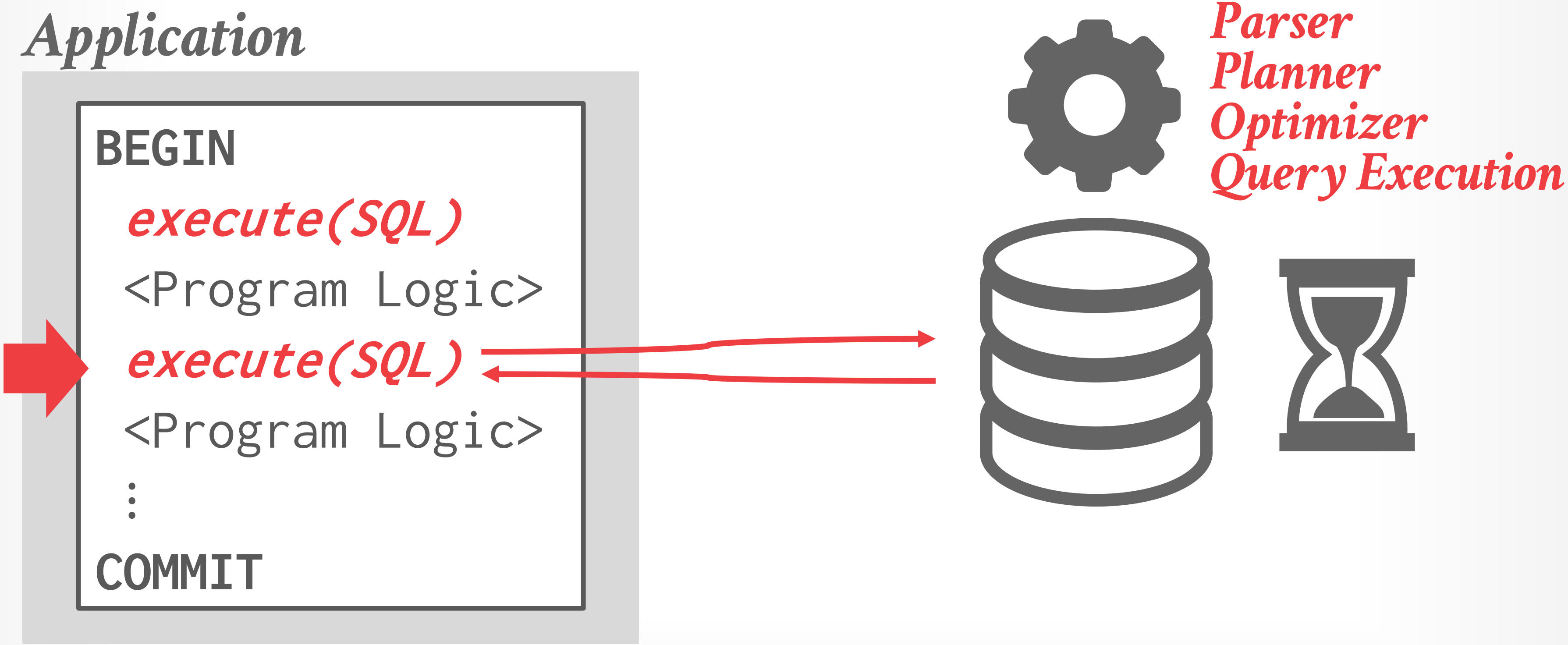


Application

```
BEGIN
  execute(SQL)
  <Program Logic>
  execute(SQL)
  <Program Logic>
  ⋮
COMMIT
```

Parser
Planner
Optimizer
Query Execution

CONVERSATIONAL DATABASE API



Application

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BEGIN
  execute(SQL)
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Parser
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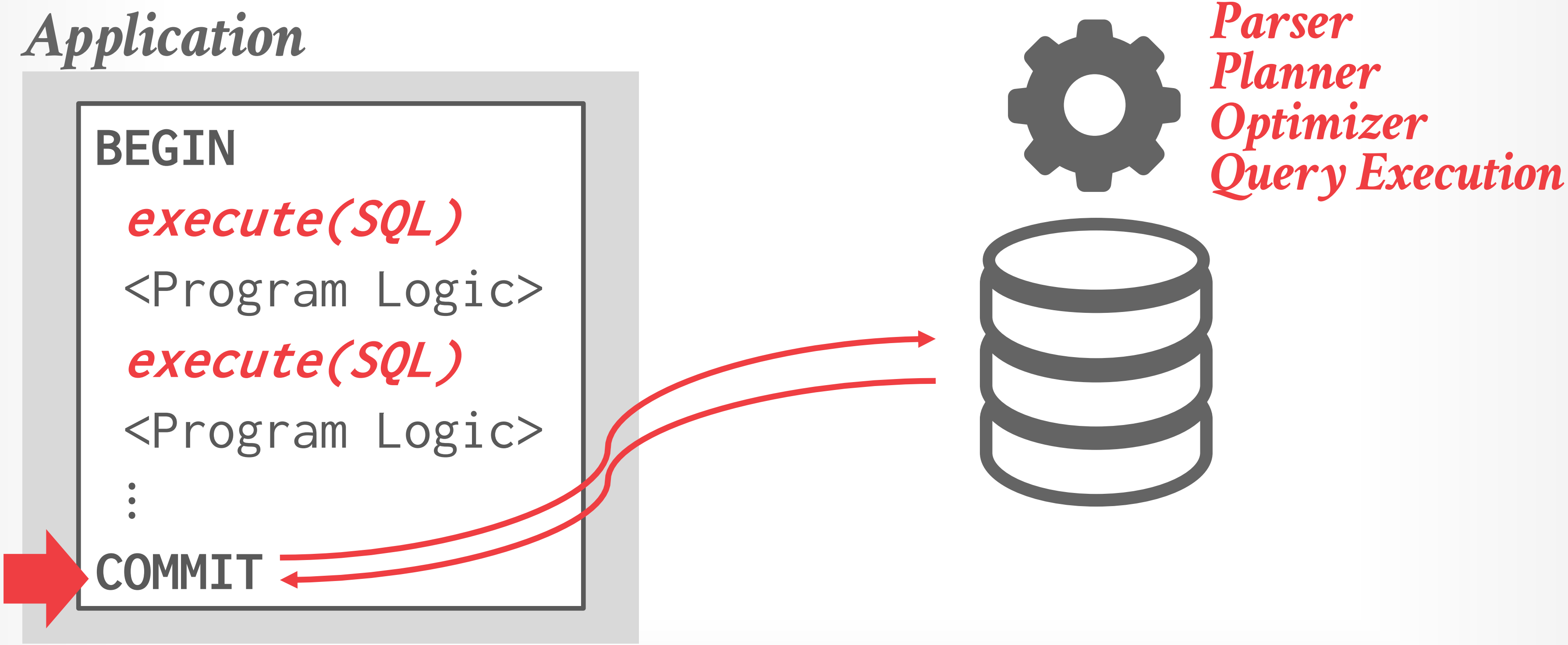
CONVERSATIONAL DATABASE API

Application



EMBEDDED DATABASE LOGIC

Moving application logic into the DBMS can (potentially) provide several benefits:

→ Fewer network round-trips (better efficiency).
→ Immediate notification of changes.
→ DBMS spends less time waiting during transactions.
→ Developers do not have to reimplement functionality.
→ Extend the functionality of the DBMS.

EMBEDDED DATABASE LOGIC

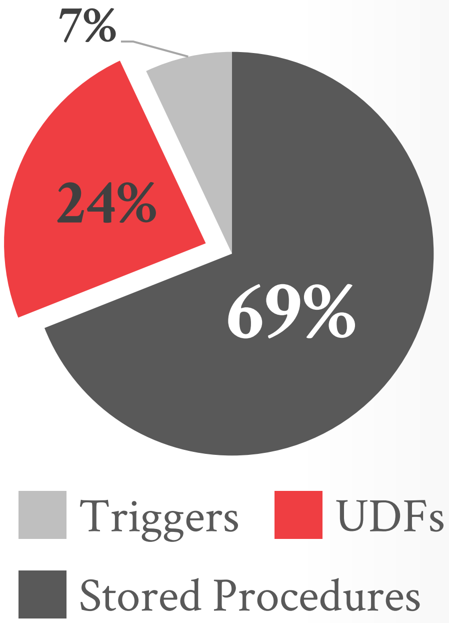
User-Defined Functions (UDFs)

Stored Procedures

Triggers

User-Defined Types (UDTs)

User-Defined Aggregates (UDAs)



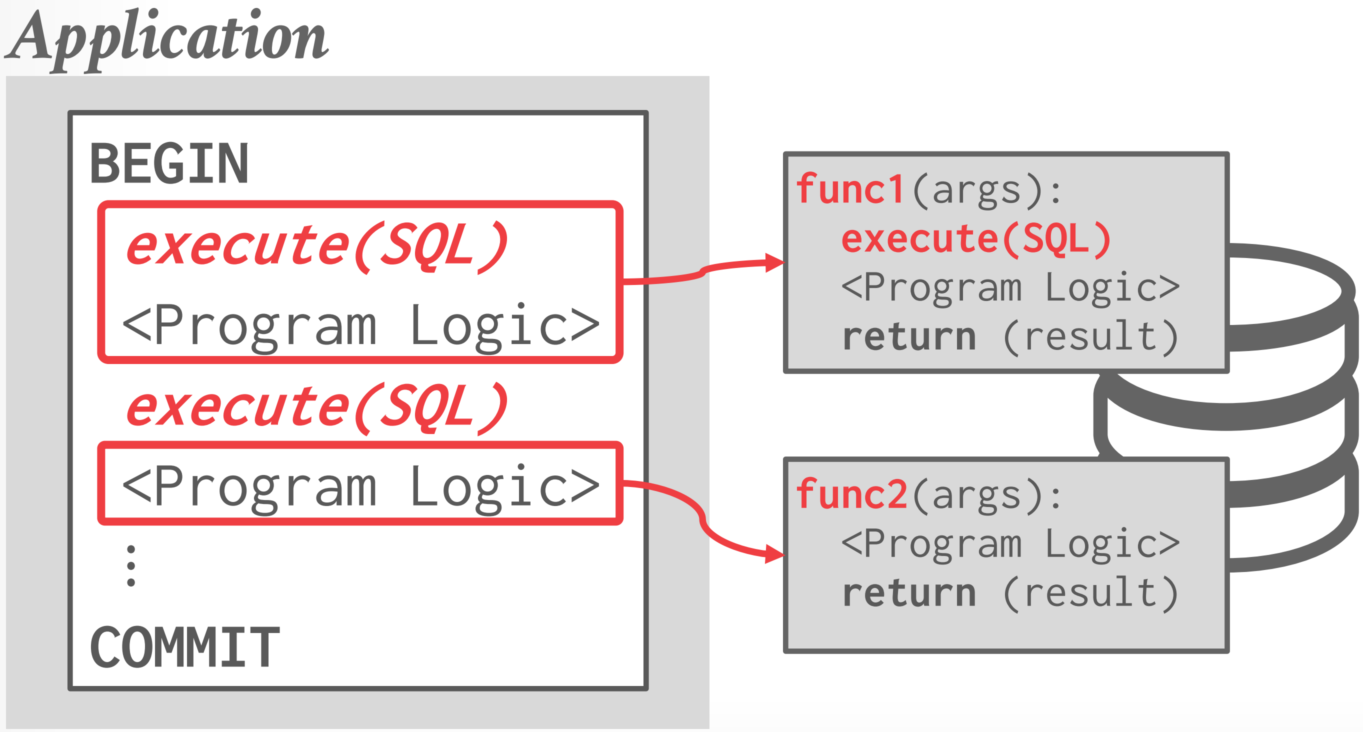
PROCEDURAL EXTENSIONS OF SQL: UNDERSTANDING THEIR USAGE IN THE WILD
VLDB 2021

USER-DEFINED FUNCTIONS

Application

```
BEGIN
  execute(SQL)
  <Program Logic>
  execute(SQL)
  <Program Logic>
  ⋮
COMMIT
```

USER-DEFINED FUNCTIONS



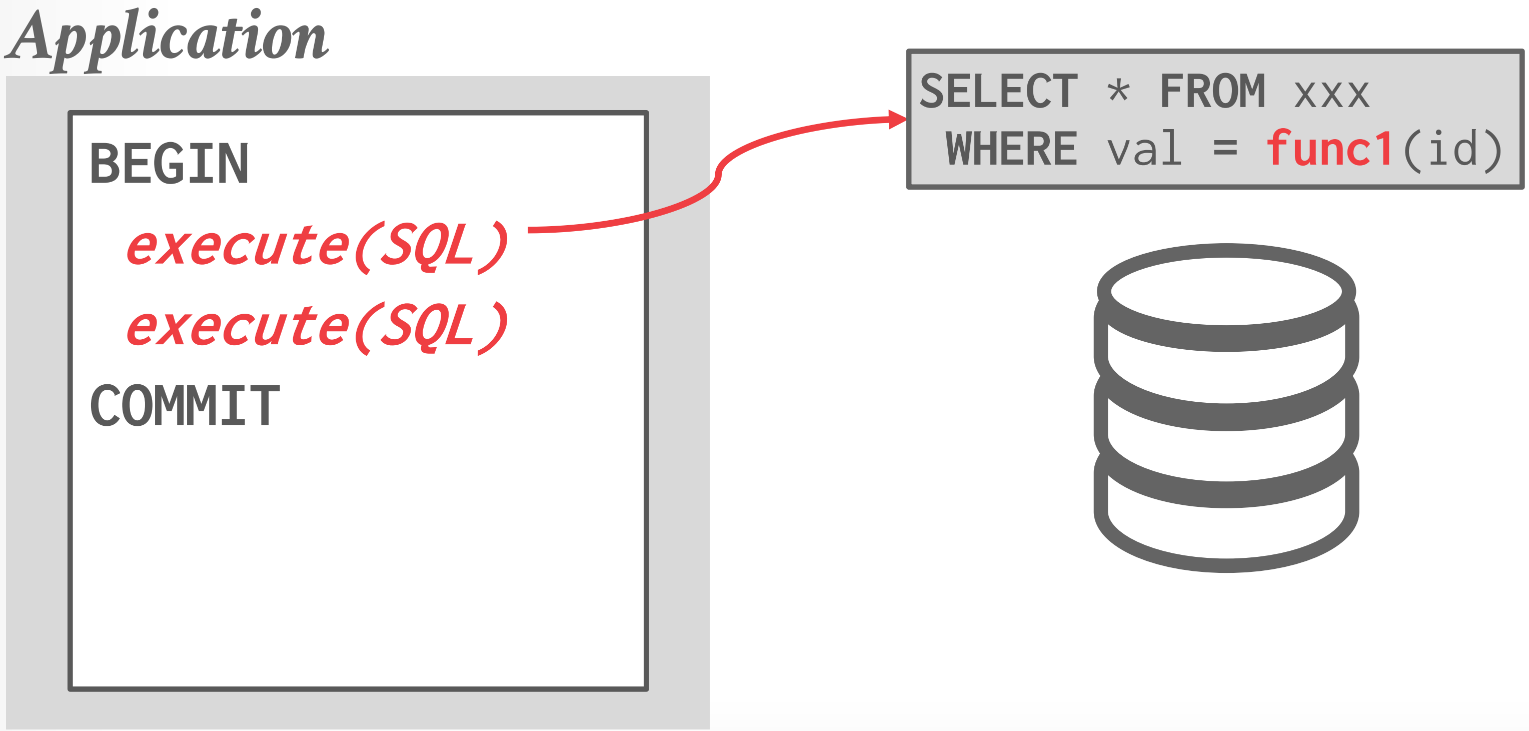
Application

```
BEGIN
execute(SQL)
<Program Logic>
execute(SQL)
<Program Logic>
⋮
COMMIT
```

```
func1(args):
  execute(SQL)
  <Program Logic>
  return (result)
```

```
func2(args):
  <Program Logic>
  return (result)
```

USER-DEFINED FUNCTIONS



Application

```
BEGIN
  execute(SQL)
  execute(SQL)
COMMIT
```

```
SELECT * FROM xxx
 WHERE val = func1(id)
```

TODAY'S AGENDA

Background

UDF In-lining

UDF CTE Conversion

Sam's Rant

USER-DEFINED FUNCTIONS

A **user-defined function** (UDF) is a function written by the application developer that extends the system's functionality beyond its built-in operations.

→ It takes in input arguments (scalars)
→ Perform some computation
→ Return a result (scalars, tables)

UDF – SQL FUNCTIONS

A SQL-based UDF contains a list of queries that the DBMS executes in order when invoked.

→ The function returns the result of the last query executed.

```
CREATE FUNCTION get_foo(int)
  RETURNS foo
  LANGUAGE SQL AS $$
  SELECT * FROM foo WHERE foo.id = $1;
$$;
```

Input Args

UDF – SQL FUNCTIONS

A SQL-based UDF contains a list of queries that the DBMS executes in order when invoked.

→ The function returns the result of the last query executed.

Return Args

```
CREATE FUNCTION get_foo(int)
  RETURNS foo
  LANGUAGE SQL AS $$
  SELECT * FROM foo WHERE foo.id = $1;
$$;
```

UDF – SQL FUNCTIONS

A SQL-based UDF contains a list of queries that the DBMS executes in order when invoked.

→ The function returns the result of the last query executed.

```
CREATE FUNCTION get_foo(int)
   RETURNS foo
   LANGUAGE SQL AS $$
   SELECT * FROM foo WHERE foo.id = $1;
$$;
```

Function Body

UDF – SQL FUNCTIONS

A SQL-based UDF contains a list of queries that the DBMS executes in order when invoked.

→ The function returns the result of the last query executed.

```
CREATE FUNCTION get_foo(int)
  RETURNS foo
  LANGUAGE SQL AS $$
  SELECT * FROM foo WHERE foo.id = $1;
$$;
```

```
SELECT get_foo(1);
```

```
SELECT * FROM get_foo(1);
```

UDF – SQL FUNCTIONS

SQL Standard provides the **ATOMIC** keyword to tell the DBMS that it should track dependencies between SQL UDFs.

```
CREATE FUNCTION get_foo(int)
  RETURNS foo
  LANGUAGE SQL
  BEGIN ATOMIC;
    SELECT * FROM foo WHERE foo.id = $1;
  END;
```

UDF – EXTERNAL PROGRAMMING LANGUAGE

Some DBMSs support writing UDFs in languages other than SQL.

→ **SQL Standard**: SQL/PSM
→ **Oracle/DB2**: PL/SQL
→ **Postgres**: PL/pgSQL
→ **DB2**: SQL PL
→ **MSSQL/Sybase**: Transact-SQL

Other systems support more common programming languages:

→ Sandbox vs. non-Sandbox

UDF – EXTERNAL PROGRAMMING LANGUAGE

```
CREATE FUNCTION cust_level(@ckey int)
RETURNS char(10) AS
BEGIN
 DECLARE @total float;
 DECLARE @level char(10);

 SELECT @total = SUM(o_totalprice)
   FROM orders WHERE o_custkey=@ckey;

 IF (@total > 1000000)
  SET @level = 'Platinum';
 ELSE
  SET @level = 'Regular';

 RETURN @level;
END
```

Get all the customer ids and compute their customer service level based on the amount of money they have spent.

```
SELECT c_custkey,
       cust_level(c_custkey)
FROM customer
```

UDF ADVANTAGES

They encourage modularity and code reuse

→ Different queries can reuse the same application logic without having to reimplement it each time.

Fewer network round-trips between application server and DBMS for complex operations.

Some types of application logic are easier to express and read as UDFs than SQL.

UDF DISADVANTAGES (1)

Query optimizers treat external programming language UDFs as black boxes.

→ DBMS is unable to estimate the function's cost / selectivity if it doesn't understand what the logic inside of it will do when it runs.

→ Example: `WHERE val = my_udf(123)`

It is difficult to parallelize UDFs due to correlated queries inside of them.

→ Some DBMSs will only execute queries with a single thread if they contain a UDF.

→ Some UDFs incrementally construct queries.

UDF DISADVANTAGES (2)

Complex UDFs in SELECT / WHERE clauses force the DBMS to execute iteratively.

→ RBAR = "Row By Agonizing Row"

→ Things get even worse if UDF invokes queries due to implicit joins that the optimizer cannot "see".

Since the DBMS executes the commands in the UDF one-by-one, it is unable to perform cross-statement optimizations.

UDF PERFORMANCE

Microsoft SQL Server

TPC-H Q12 using a UDF (SF=1).

```
SELECT l_shipmode,
       SUM(CASE
           WHEN o_orderpriority <> '1-URGENT'
           THEN 1 ELSE 0 END
       ) AS low_line_count
  FROM orders, lineitem
 WHERE o_orderkey = l_orderkey
   AND l_shipmode IN ('MAIL','SHIP')
   AND l_commitdate < l_receiptdate
   AND l_shipdate < l_commitdate
   AND l_receiptdate >= '1994-01-01'
   AND dbo.cust_name(o_custkey) IS NOT NULL
 GROUP BY l_shipmode
 ORDER BY l_shipmode
```

Source: Karthik Ramachandra

UDF PERFORMANCE

Microsoft SQL Server

TPC-H Q12 using a UDF (SF=1).

→ **Original Query:** 0.8 sec

→ **Query + UDF:** 13 hr 30 min

```
SELECT l_shipmode,
       SUM(CASE
           WHEN o_orderpriority <> '1-URGENT'
           THEN 1 ELSE 0 END
       ) AS low_line_count
  FROM orders, lineitem
 WHERE o_orderkey = l_orderkey
   AND l_shipmode IN ('MAIL','SHIP')
   AND l_commitdate < l_receiptdate
   AND l_shipdate < l_commitdate
   AND l_receiptdate >= '1994-01-01'
   AND dbo.cust_name(o_custkey) IS NOT NULL
 GROUP BY l_shipmode
 ORDER BY l_shipmode
```

```
CREATE FUNCTION cust_name(@ckey int)
RETURNS char(25) AS
BEGIN
 DECLARE @n char(25);
 SELECT @n = c_name
   FROM customer WHERE c_custkey = @ckey;
 RETURN @n;
END
```

Source: Karthik Ramachandra

UDF Acceleration

Approach #1: Compilation

→ Compile interpreted UDF code into native machine code.

→ Can inline UDF into compiled query plan if the DBMS supports holistic query compilation (e.g., HyPer).

Approach #2: Parallelization

→ Rely on user-defined annotations to determine which portions of a UDF can be safely executed in parallel.

Approach #3: Inlining

→ Convert UDF into declarative form and then inline it into the calling query.

Source: Surabhi Gupta

MICROSOFT SQL SERVER UDF HISTORY

2001 – Microsoft adds TSQL Scalar UDFs.

Source: Karthik Ramachandra

MICROSOFT SQL SERVER UDF HISTORY

2001 – Microsoft adds TSQL Scalar UDFs.

2008 – People realize that UDFs are "evil".

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MICROSOFT SQL SERVER UDF HISTORY

Fs.

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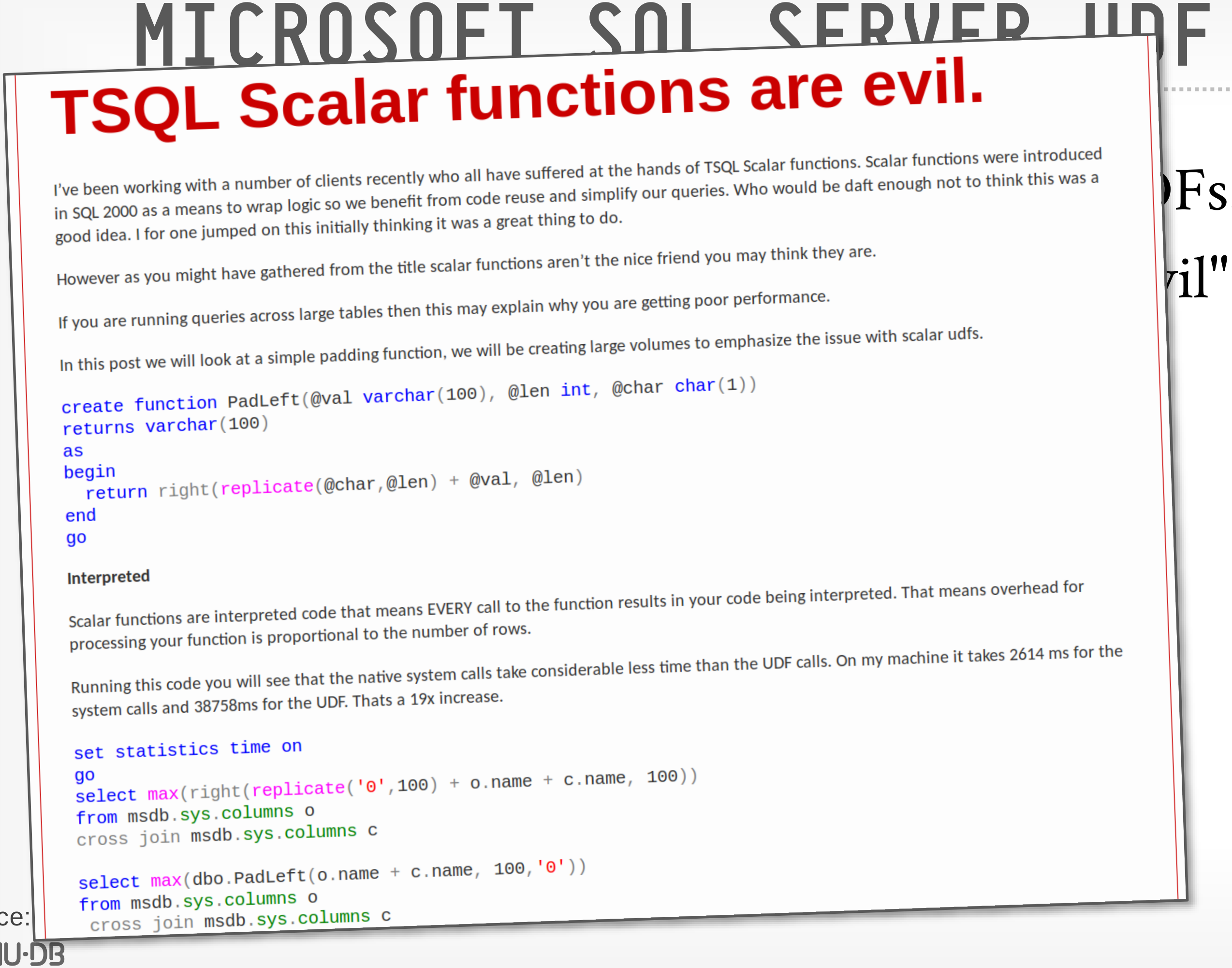


TSQL Scalar functions are evil.

I've been working with a number of clients recently who all have suffered at the hands of TSQL Scalar functions. Scalar functions were introduced in SQL 2000 as a means to wrap logic so we benefit from code reuse and simplify our queries. Who would be daft enough not to think this was a good idea. I for one jumped on this initially thinking it was a great thing to do.

However as you might have gathered from the title scalar functions aren't the nice friend you may think they are.

If you are running queries across large tables then this may explain why you are getting poor performance.

In this post we will look at a simple padding function, we will be creating large volumes to emphasize the issue with scalar udfs.

```
create function PadLeft(@val varchar(100), @len int, @char char(1))
returns varchar(100)
as
begin
  return right(replicate(@char,@len) + @val, @len)
end
go
```

Interpreted

Scalar functions are interpreted code that means EVERY call to the function results in your code being interpreted. That means overhead for processing your function is proportional to the number of rows.

Running this code you will see that the native system calls take considerable less time than the UDF calls. On my machine it takes 2614 ms for the system calls and 38758ms for the UDF. Thats a 19x increase.

```
set statistics time on
go
select max(right(replicate('0',100) + o.name + c.name, 100))
from msdb.sys.columns o
cross join msdb.sys.columns c

select max(dbo.PadLeft(o.name + c.name, 100,'0'))
from msdb.sys.columns o
 cross join msdb.sys.columns c
```

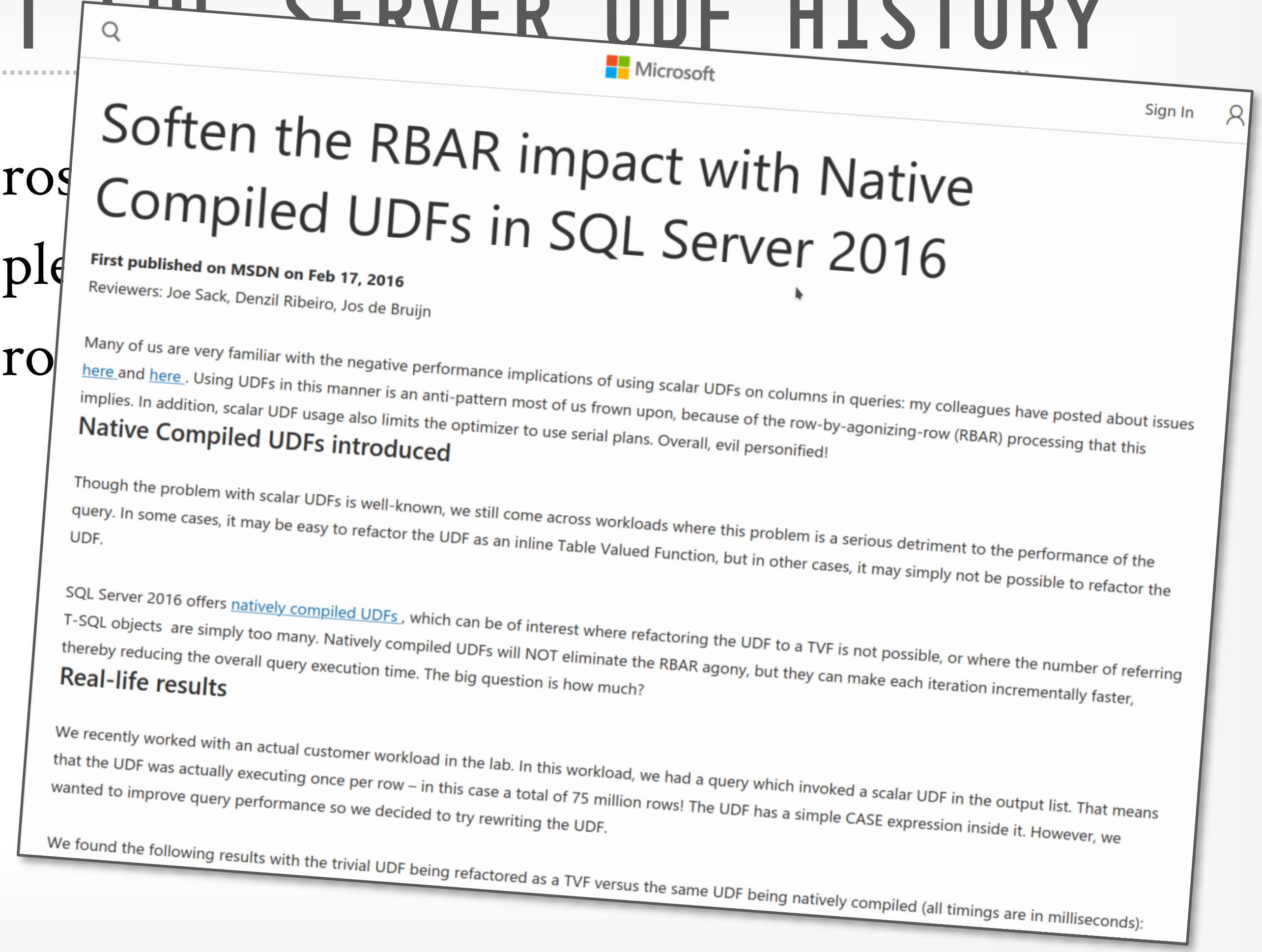
Source:

MICROSOFT SQL SERVER UDF HISTORY

2001 – Micros

2008 – People

2010 – Micro



Soften the RBAR impact with Native Compiled UDFs in SQL Server 2016

First published on MSDN on Feb 17, 2016

Reviewers: Joe Sack, Denzil Ribeiro, Jos de Bruijn

Many of us are very familiar with the negative performance implications of using scalar UDFs on columns in queries: my colleagues have posted about issues here and here . Using UDFs in this manner is an anti-pattern most of us frown upon, because of the row-by-agonizing-row (RBAR) processing that this implies. In addition, scalar UDF usage also limits the optimizer to use serial plans. Overall, evil personified!

Native Compiled UDFs introduced

Though the problem with scalar UDFs is well-known, we still come across workloads where this problem is a serious detriment to the performance of the query. In some cases, it may be easy to refactor the UDF as an inline Table Valued Function, but in other cases, it may simply not be possible to refactor the UDF.

SQL Server 2016 offers natively compiled UDFs , which can be of interest where refactoring the UDF to a TVF is not possible, or where the number of referring T-SQL objects are simply too many. Natively compiled UDFs will NOT eliminate the RBAR agony, but they can make each iteration incrementally faster, thereby reducing the overall query execution time. The big question is how much?

Real-life results

We recently worked with an actual customer workload in the lab. In this workload, we had a query which invoked a scalar UDF in the output list. That means that the UDF was actually executing once per row – in this case a total of 75 million rows! The UDF has a simple CASE expression inside it. However, we wanted to improve query performance so we decided to try rewriting the UDF.

We found the following results with the trivial UDF being refactored as a TVF versus the same UDF being natively compiled (all timings are in milliseconds):

Source: Karthik Ramachandra

MICROSOFT SQL SERVER UDF HISTORY

2001 – Microsoft adds TSQL Scalar UDFs.

2008 – People realize that UDFs are "evil".

2010 – Microsoft acknowledges that UDFs are evil.

2014 – UDF decorrelation research @ IIT-B.

Source: Karthik Ramachandra

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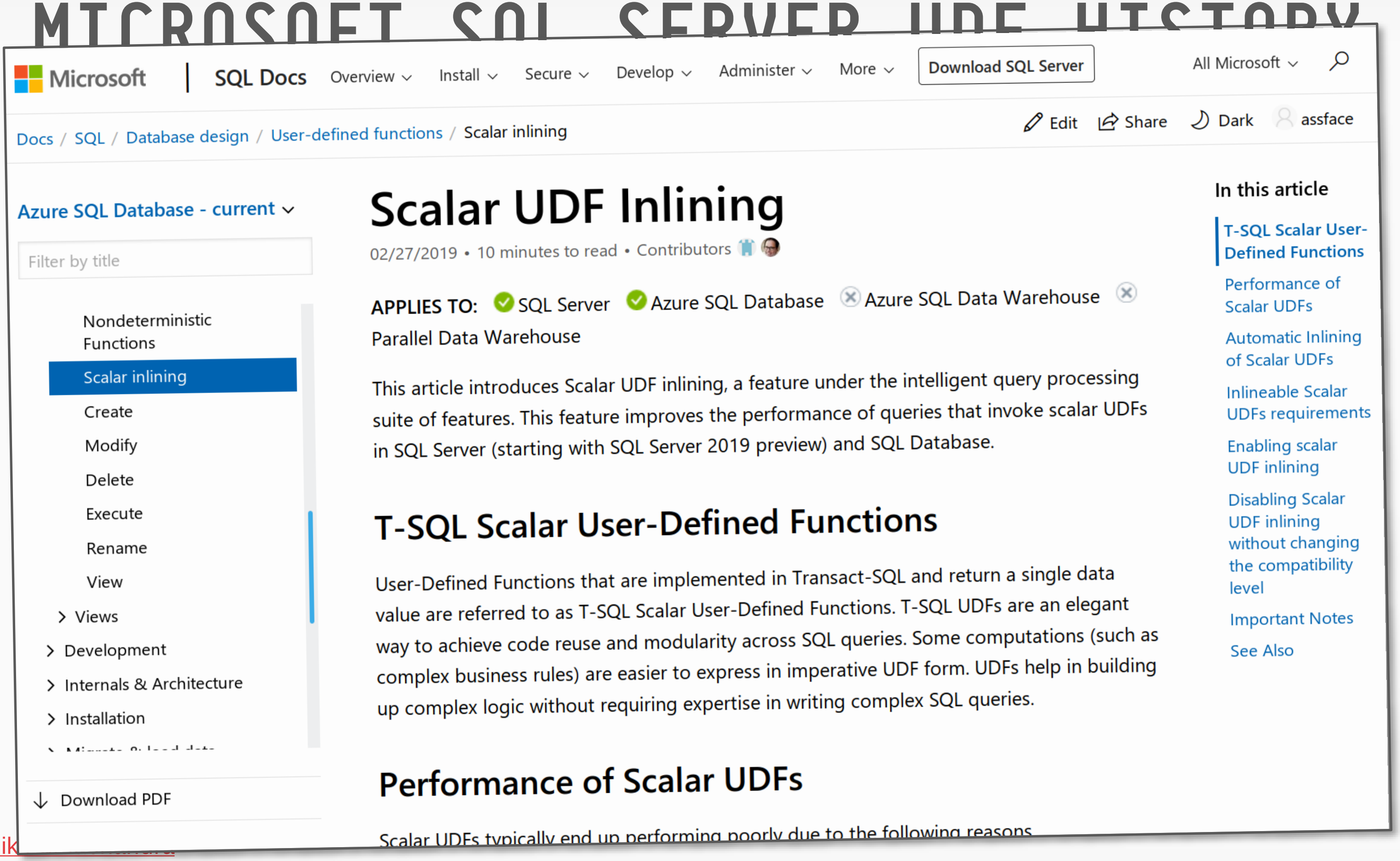
2014 – UDF decorrelation research @ IIT-B.

2015 – Froid project begins @ MSFT Gray Lab.

2018 – Froid added to SQL Server 2019.

Source: Karthik Ramachandra

MICROSOFT SQL SERVER UDF HISTORY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Migrate & load data
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In this article
T-SQL Scalar User-Defined Functions
Performance of Scalar UDFs
Automatic Inlining of Scalar UDFs
Inlineable Scalar UDFs requirements
Enabling scalar UDF inlining
Disabling Scalar UDF inlining without changing the compatibility level
Important Notes
See Also

Scalar UDF Inlining

02/27/2019 • 10 minutes to read • Contributors

APPLIES TO: ✓ SQL Server ✓ Azure SQL Database ☒ Azure SQL Data Warehouse ☒ Parallel Data Warehouse

This article introduces Scalar UDF inlining, a feature under the intelligent query processing suite of features. This feature improves the performance of queries that invoke scalar UDFs in SQL Server (starting with SQL Server 2019 preview) and SQL Database.

T-SQL Scalar User-Defined Functions

User-Defined Functions that are implemented in Transact-SQL and return a single data value are referred to as T-SQL Scalar User-Defined Functions. T-SQL UDFs are an elegant way to achieve code reuse and modularity across SQL queries. Some computations (such as complex business rules) are easier to express in imperative UDF form. UDFs help in building up complex logic without requiring expertise in writing complex SQL queries.

Performance of Scalar UDFs

Scalar UDFs typically end up performing poorly due to the following reasons

Source: Karthik

FROID

Automatically convert UDFs into relational algebra expressions that are inlined as sub-queries.

→ Does not require the app developer to change UDF code.

Perform conversion during the rewrite phase to avoid having to change the cost-base optimizer.

→ Commercial DBMSs already have powerful transformation rules for executing sub-queries efficiently.

FROID: OPTIMIZATION OF IMPERATIVE PROGRAMS IN A RELATIONAL DATABASE
VLDB 2017

SUB-QUERIES

The DBMS treats nested sub-queries in the where clause as functions that take parameters and return a single value or set of values.

Two Approaches:

→ Rewrite to de-correlate and/or flatten them

→ Decompose nested query and store result to temporary table. Then the outer joins with the temporary table.

SUB-QUERIES – REWRITE

```
SELECT user_id FROM orders AS o1
 WHERE EXISTS(
    SELECT COUNT(*) FROM orders AS o2
     WHERE o1.user_id = o2.user_id
  GROUP BY o2.user_id HAVING COUNT(*) >= 2
 )
 ORDER BY user_id ASC LIMIT 1;
```

```
SELECT user_id FROM orders
 GROUP BY user_id
HAVING COUNT(*) >= 2
 ORDER BY user_id ASC LIMIT 1;
```

Example: Retrieve the first user that has made at least two purchases.

LATERAL JOIN

A lateral inner subquery can refer to fields in rows of the table reference to determine which rows to return.

→ Allows you to have sub-queries in **FROM** clause.

The DBMS iterates through each row in the table referenced and evaluates the inner sub-query for each row.

→ The rows returned by the inner sub-query are added to the result of the join with the outer query.

LATERAL JOIN - EXAMPLE

```
SELECT user_id, first_order, next_order, id
  FROM (SELECT user_id,
               MIN(created) AS first_order
          FROM orders GROUP BY user_id) AS o1
  INNER JOIN LATERAL
        (SELECT id, created AS next_order
           FROM orders
          WHERE user_id = o1.user_id
            AND created > o1.first_order
          ORDER BY created ASC LIMIT 1) AS o2
    ON true
 LIMIT 1;
```

Example: Retrieve the first user that has made at least two purchases along with the timestamps of the first and next orders.

Source: Krzysztof Kempiński

LATERAL JOIN - EXAMPLE

```
SELECT user_id, first_order, next_order, id
  FROM (SELECT user_id,
               MIN(created) AS first_order
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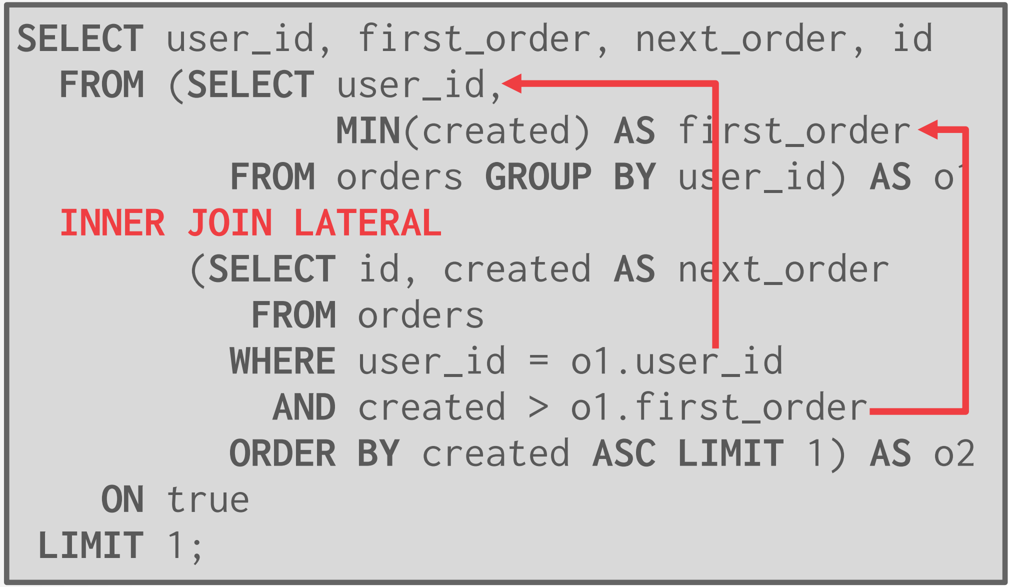

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    ON true
 LIMIT 1;
```

Example: Retrieve the first user that has made at least two purchases along with the timestamps of the first and next orders.

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FROID OVERVIEW

Step #1 – Transform Statements

Step #2 – Break UDF into Regions

Step #3 – Merge Expressions

Step #4 – Inline UDF Expression into Query

Step #5 – Run Updated Query through Optimizer

STEP #1 – TRANSFORM STATEMENTS

Imperative Statements

SQL Statements

```
SET @level = 'Platinum';
```

```
SELECT 'Platinum' AS level;
```

```
SELECT @total = SUM(o_totalprice)
  FROM orders
 WHERE o_custkey=@ckey;
```

```
SELECT (
  SELECT SUM(o_totalprice)
    FROM orders
   WHERE o_custkey=@ckey
) AS total;
```

```
IF (@total > 1000000)
    SET @level = 'Platinum';
```

```
SELECT (
  CASE WHEN total > 1000000
    THEN 'Platinum'
    ELSE NULL
  END) AS level;
```

Source: Karthik Ramachandra

STEP #2 – BREAK INTO REGIONS

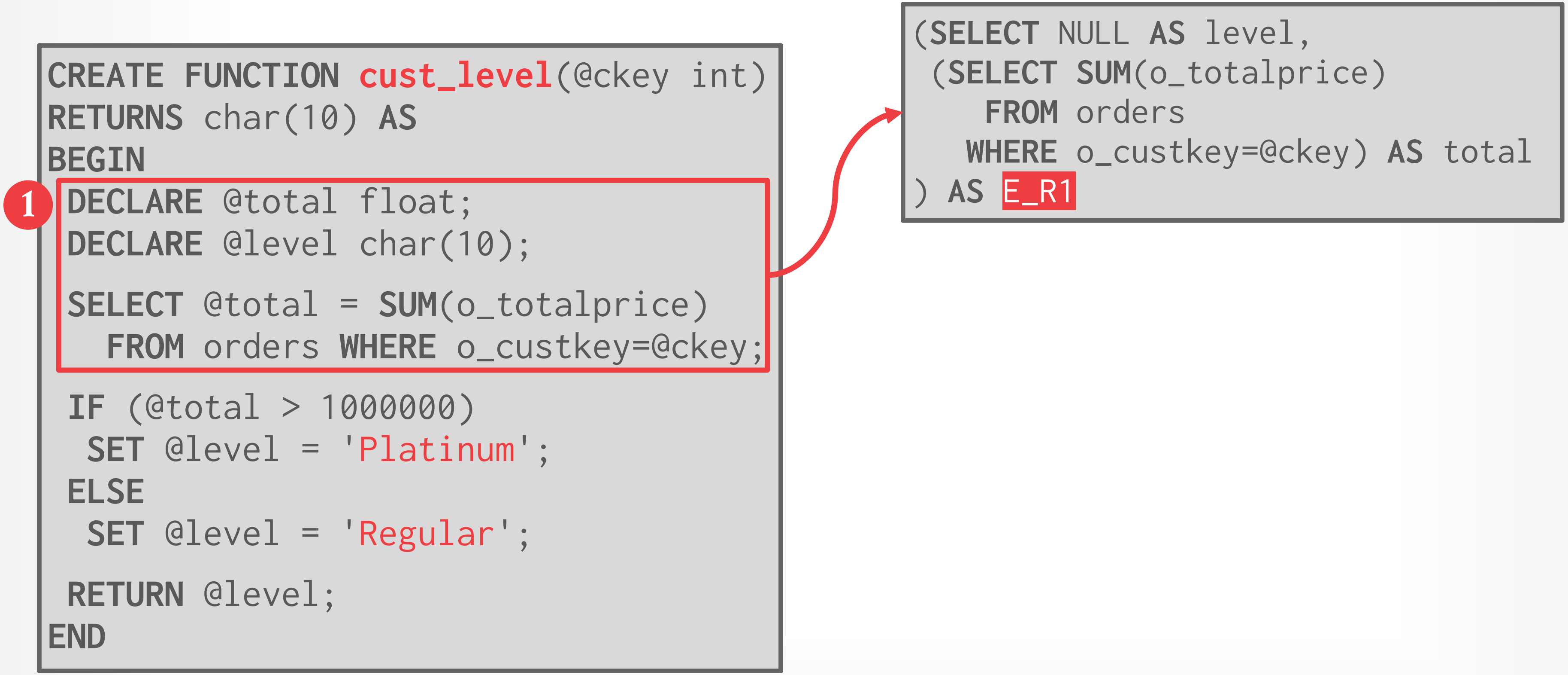
```
CREATE FUNCTION cust_level(@ckey int)
RETURNS char(10) AS
BEGIN
 DECLARE @total float;
 DECLARE @level char(10);

 SELECT @total = SUM(o_totalprice)
   FROM orders WHERE o_custkey=@ckey;

 IF (@total > 1000000)
  SET @level = 'Platinum';
 ELSE
  SET @level = 'Regular';

 RETURN @level;
END
```

STEP #2 – BREAK INTO REGIONS



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 DECLARE @level char(10);

 SELECT @total = SUM(o_totalprice)
   FROM orders WHERE o_custkey=@ckey;

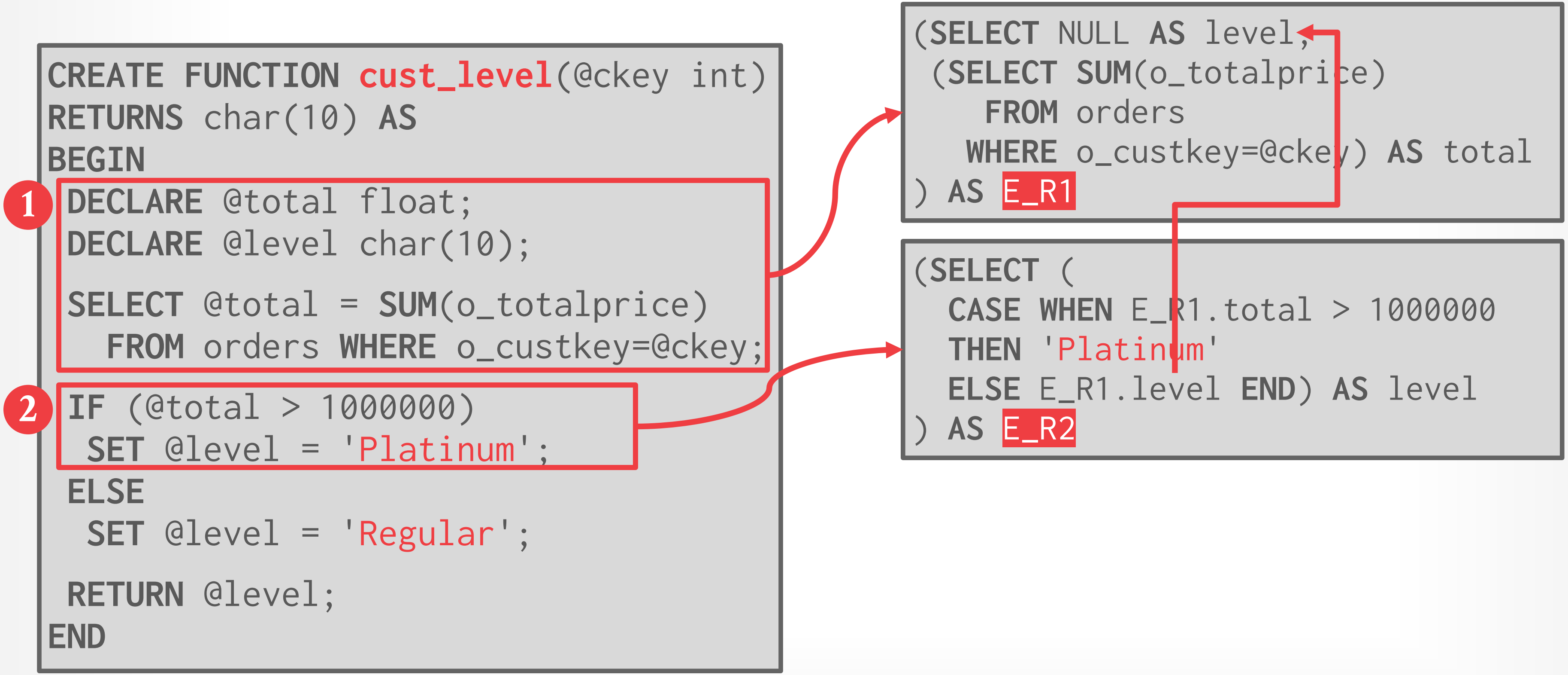
 IF (@total > 1000000)
  SET @level = 'Platinum';
 ELSE
  SET @level = 'Regular';

 RETURN @level;
END
```

1

```
(SELECT NULL AS level,
 (SELECT SUM(o_totalprice)
    FROM orders
   WHERE o_custkey=@ckey) AS total
) AS E_R1
```

STEP #2 – BREAK INTO REGIONS



```
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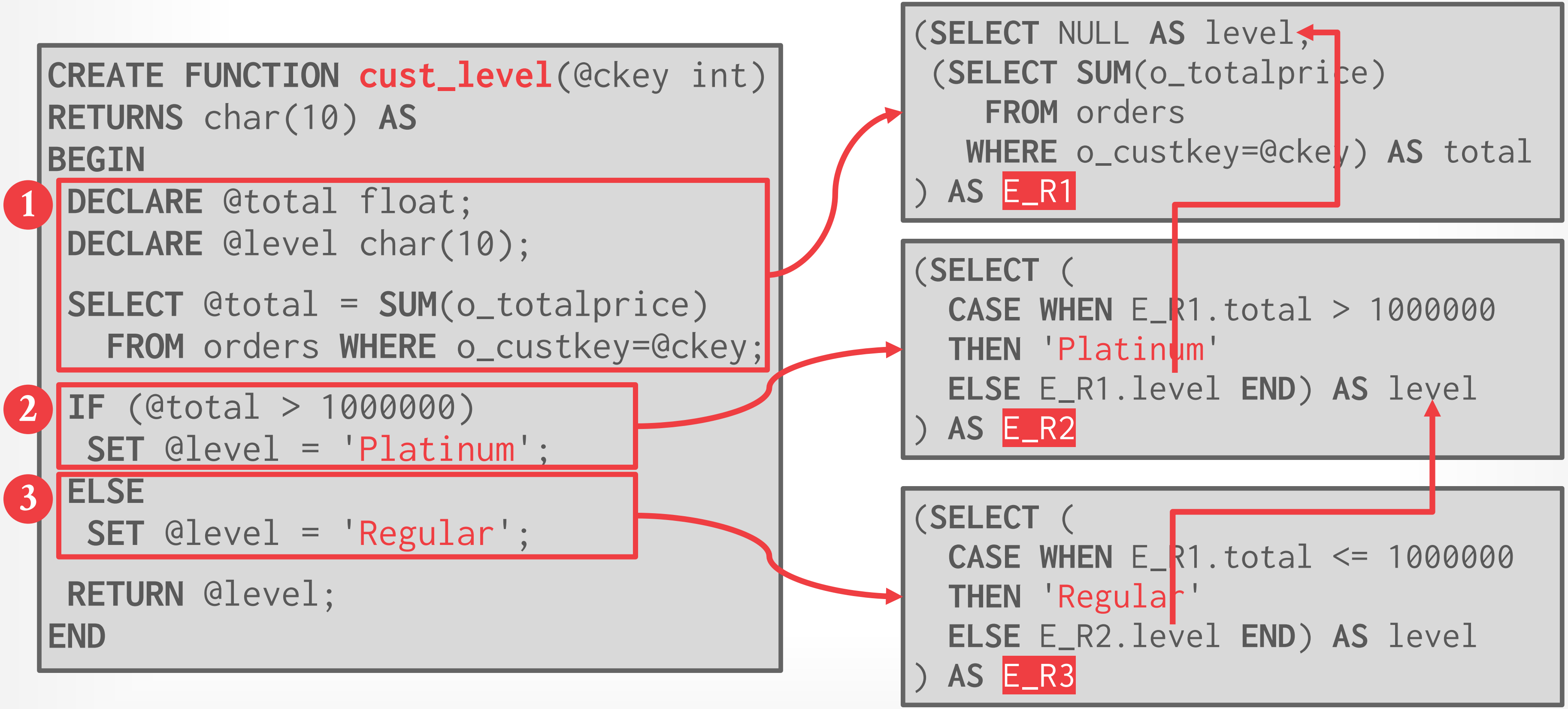
   FROM orders WHERE o_custkey=@ckey;
 IF (@total > 1000000)
  SET @level = 'Platinum';
 ELSE
  SET @level = 'Regular';

 RETURN @level;
END
```

```
(SELECT NULL AS level,
 (SELECT SUM(o_totalprice)
    FROM orders
   WHERE o_custkey=@ckey) AS total
) AS E_R1
```

```
(SELECT (
  CASE WHEN E_R1.total > 1000000
  THEN 'Platinum'
  ELSE E_R1.level END) AS level
) AS E_R2
```

STEP #2 – BREAK INTO REGIONS



```
CREATE FUNCTION cust_level(@ckey int)
RETURNS char(10) AS
BEGIN
1  DECLARE @total float;
   DECLARE @level char(10);

   SELECT @total = SUM(o_totalprice)
     FROM orders WHERE o_custkey=@ckey;
2  IF (@total > 1000000)
    SET @level = 'Platinum';
3  ELSE
    SET @level = 'Regular';

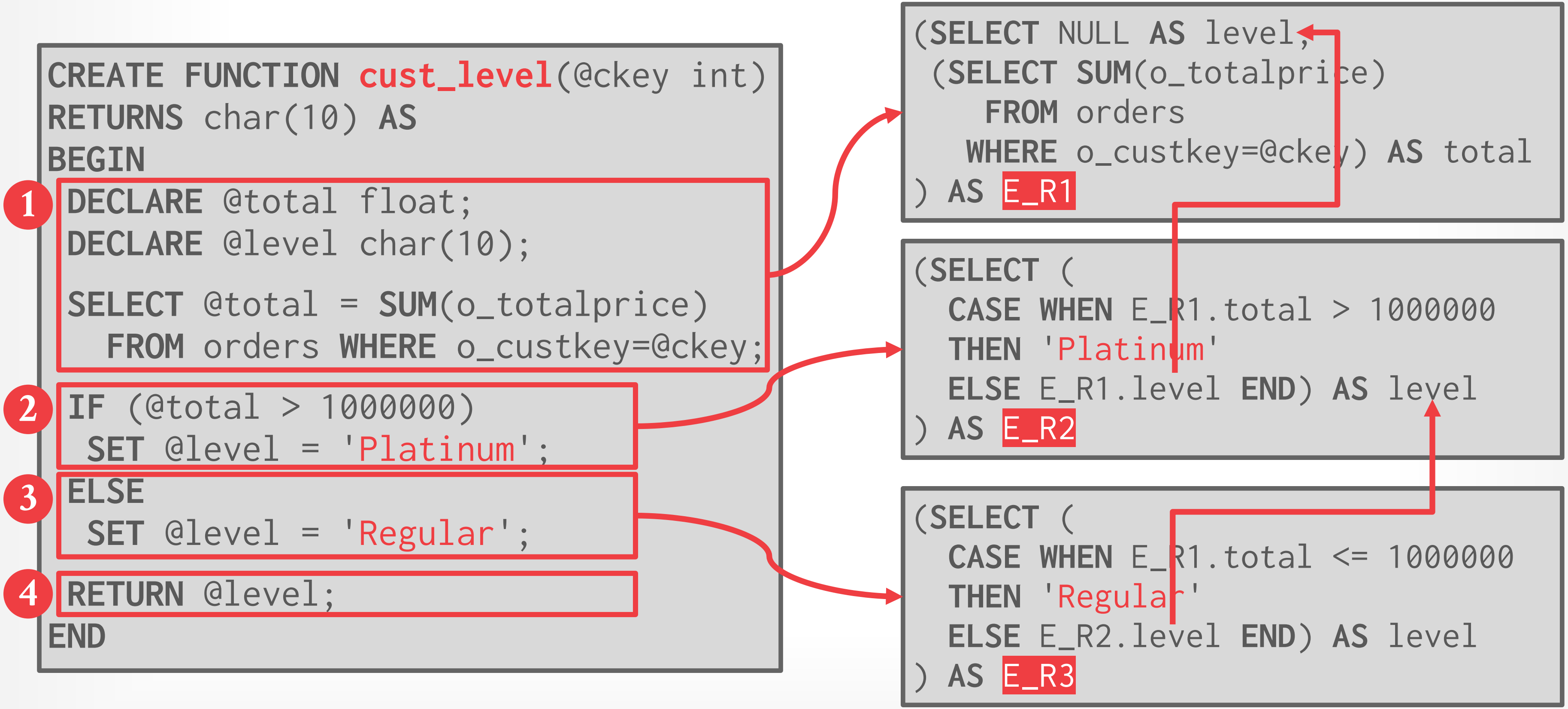
 RETURN @level;
END
```

```
(SELECT NULL AS level,
 (SELECT SUM(o_totalprice)
    FROM orders
   WHERE o_custkey=@ckey) AS total
) AS E_R1
```

```
(SELECT (
  CASE WHEN E_R1.total > 1000000
  THEN 'Platinum'
  ELSE E_R1.level END) AS level
) AS E_R2
```

```
(SELECT (
  CASE WHEN E_R1.total <= 1000000
  THEN 'Regular'
  ELSE E_R2.level END) AS level
) AS E_R3
```

STEP #2 – BREAK INTO REGIONS



```
CREATE FUNCTION cust_level(@ckey int)
RETURNS char(10) AS
BEGIN
```

1

```
 DECLARE @total float;
 DECLARE @level char(10);

 SELECT @total = SUM(o_totalprice)
   FROM orders WHERE o_custkey=@ckey;
```

2

```
 IF (@total > 1000000)
  SET @level = 'Platinum';
```

3

```
 ELSE
  SET @level = 'Regular';
```

4

```
 RETURN @level;
END
```

```
(SELECT NULL AS level,
 (SELECT SUM(o_totalprice)
    FROM orders
   WHERE o_custkey=@ckey) AS total
) AS E_R1
```

```
(SELECT (
  CASE WHEN E_R1.total > 1000000
  THEN 'Platinum'
  ELSE E_R1.level END) AS level
) AS E_R2
```

```
(SELECT (
  CASE WHEN E_R1.total <= 1000000
  THEN 'Regular'
  ELSE E_R2.level END) AS level
) AS E_R3
```

STEP #3 – MERGE EXPRESSIONS

```
(SELECT NULL AS level,
 (SELECT SUM(o_totalprice)
    FROM orders
   WHERE o_custkey=@ckey) AS total
) AS E_R1
```

```
(SELECT (
  CASE WHEN E_R1.total > 1000000
  THEN 'Platinum'
  ELSE E_R1.level END) AS level
) AS E_R2
```

```
(SELECT (
  CASE WHEN E_R1.total <= 1000000
  THEN 'Regular'
  ELSE E_R2.level END) AS level
) AS E_R3
```

```
SELECT E_R3.level FROM
 (SELECT NULL AS level,
  (SELECT SUM(o_totalprice)
     FROM orders
    WHERE o_custkey=@ckey) AS total
 ) AS E_R1
CROSS APPLY
 (SELECT (
   CASE WHEN E_R1.total > 1000000
   THEN 'Platinum'
   ELSE E_R1.level END) AS level
 ) AS E_R2
CROSS APPLY
 (SELECT (
   CASE WHEN E_R1.total <= 1000000
   THEN 'Regular'
   ELSE E_R2.level END) AS level
 ) AS E_R3;
```

STEP #3 – MERGE EXPRESSIONS

```
(SELECT NULL AS level,
 (SELECT SUM(o_totalprice)
    FROM orders
   WHERE o_custkey=@ckey) AS total
) AS E_R1
```

```
(SELECT (
  CASE WHEN E_R1.total > 1000000
  THEN 'Platinum'
  ELSE E_R1.level END) AS level
) AS E_R2
```

```
(SELECT (
  CASE WHEN E_R1.total <= 1000000
  THEN 'Regular'
  ELSE E_R2.level END) AS level
) AS E_R3
```

4

```
SELECT E_R3.level FROM
 (SELECT NULL AS level,
  (SELECT SUM(o_totalprice)
     FROM orders
    WHERE o_custkey=@ckey) AS total
 ) AS E_R1
CROSS APPLY
 (SELECT (
   CASE WHEN E_R1.total > 1000000
   THEN 'Platinum'
   ELSE E_R1.level END) AS level
 ) AS E_R2
CROSS APPLY
 (SELECT (
   CASE WHEN E_R1.total <= 1000000
   THEN 'Regular'
   ELSE E_R2.level END) AS level
 ) AS E_R3;
```

STEP #4 – INLINE EXPRESSION

Original Query

```
SELECT c_custkey,
       cust_level(c_custkey)
FROM customer
```

```
  SELECT c_custkey, (
4  SELECT E_R3.level FROM
    (SELECT NULL AS level,
     (SELECT SUM(o_totalprice)
1       FROM orders
       WHERE o_custkey=@ckey) AS total
    ) AS E_R1
   CROSS APPLY
    (SELECT (
      CASE WHEN E_R1.total > 1000000
2     THEN 'Platinum'
      ELSE E_R1.level END) AS level
    ) AS E_R2
   CROSS APPLY
    (SELECT (
      CASE WHEN E_R1.total <= 1000000
3     THEN 'Regular'
      ELSE E_R2.level END) AS level
    ) AS E_R3;
  ) FROM customer;
```

STEP #5 - OPTIMIZE

```
SELECT c_custkey, (
 SELECT E_R3.level FROM
  (SELECT NULL AS level,
   (SELECT SUM(o_totalprice)
      FROM orders
     WHERE o_custkey=@ckey) AS total
  ) AS E_R1
 CROSS APPLY
  (SELECT (
    CASE WHEN E_R1.total > 1000000
    THEN 'Platinum'
    ELSE E_R1.level END) AS level
  ) AS E_R2
 CROSS APPLY
  (SELECT (
    CASE WHEN E_R1.total <= 1000000
    THEN 'Regular'
    ELSE E_R2.level END) AS level
  ) AS E_R3;
) FROM customer;
```

STEP #5 - OPTIMIZE

```
SELECT c_custkey, (
 SELECT E_R3.level FROM
  (SELECT NULL AS level,
   (SELECT SUM(o_totalprice)
      FROM orders
     WHERE o_custkey=@ckey) AS total
  ) AS E_R1
 CROSS APPLY
  (SELECT (
    CASE WHEN E_R1.total > 1000000
    THEN 'Platinum'
    ELSE E_R1.level END) AS level
  ) AS E_R2
 CROSS APPLY
  (SELECT (
    CASE WHEN E_R1.total <= 1000000
    THEN 'Regular'
    ELSE E_R2.level END) AS level
  ) AS E_R3;
) FROM customer;
```

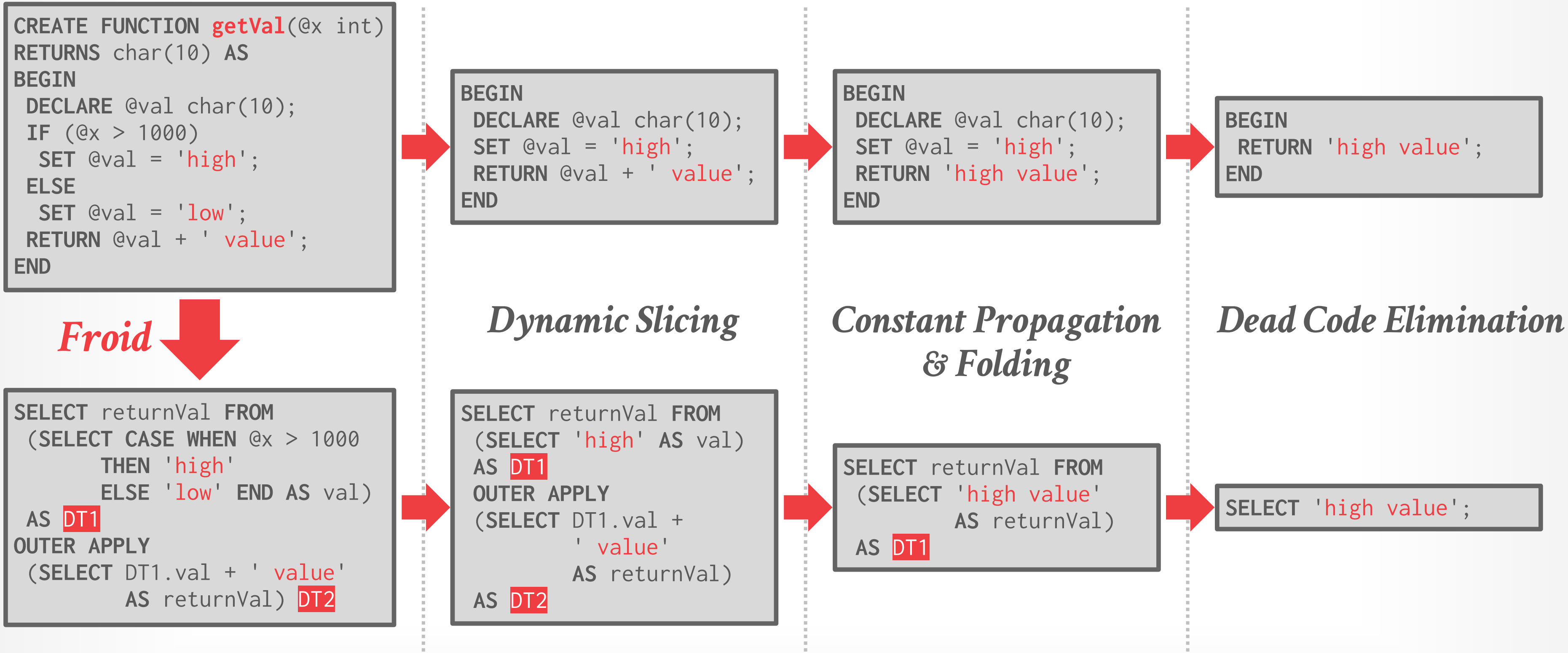
```
SELECT c.c_custkey,
       CASE WHEN e.total > 1000000
            THEN 'Platinum'
            ELSE 'Regular'
       END
  FROM customer c LEFT OUTER JOIN
     (SELECT o_custkey,
             SUM(o_totalprice) AS total
        FROM order GROUP BY o_custkey
     ) AS e
    ON c.c_custkey=e.o_custkey;
```

BONUS OPTIMIZATIONS

```
CREATE FUNCTION getVal(@x int)
RETURNS char(10) AS
BEGIN
 DECLARE @val char(10);
 IF (@x > 1000)
  SET @val = 'high';
 ELSE
  SET @val = 'low';
 RETURN @val + ' value';
END
```

```
SELECT getVal(5000);
```

BONUS OPTIMIZATIONS



```
CREATE FUNCTION getVal(@x int)
RETURNS char(10) AS
BEGIN
 DECLARE @val char(10);
 IF (@x > 1000)
  SET @val = 'high';
 ELSE
  SET @val = 'low';
 RETURN @val + ' value';
END
```

Froid

```
SELECT returnVal FROM
 (SELECT CASE WHEN @x > 1000
        THEN 'high'
        ELSE 'low' END AS val)
 AS DT1
OUTER APPLY
 (SELECT DT1.val + ' value'
         AS returnVal) DT2
```

Dynamic Slicing

```
BEGIN
 DECLARE @val char(10);
 SET @val = 'high';
 RETURN @val + ' value';
END
```

```
SELECT returnVal FROM
 (SELECT 'high' AS val)
 AS DT1
 OUTER APPLY
 (SELECT DT1.val +
         ' value'
         AS returnVal)
 AS DT2
```

Constant Propagation & Folding

```
BEGIN
 DECLARE @val char(10);
 SET @val = 'high';
 RETURN 'high value';
END
```

```
SELECT returnVal FROM
 (SELECT 'high value'
         AS returnVal)
 AS DT1
```

Dead Code Elimination

```
BEGIN
 RETURN 'high value';
END
```

```
SELECT 'high value';
```

SUPPORTED OPERATIONS (2019)

T-SQL Syntax:

→ **DECLARE**, **SET** (variable declaration, assignment)

→ **SELECT** (SQL query, assignment)

→ **IF** / **ELSE** / **ELSE IF** (arbitrary nesting)

→ **RETURN** (multiple occurrences)

→ **EXISTS**, **NOT EXISTS**, **ISNULL**, **IN**, … (Other relational algebra operations)

UDF invocation (nested/recursive with configurable depth)

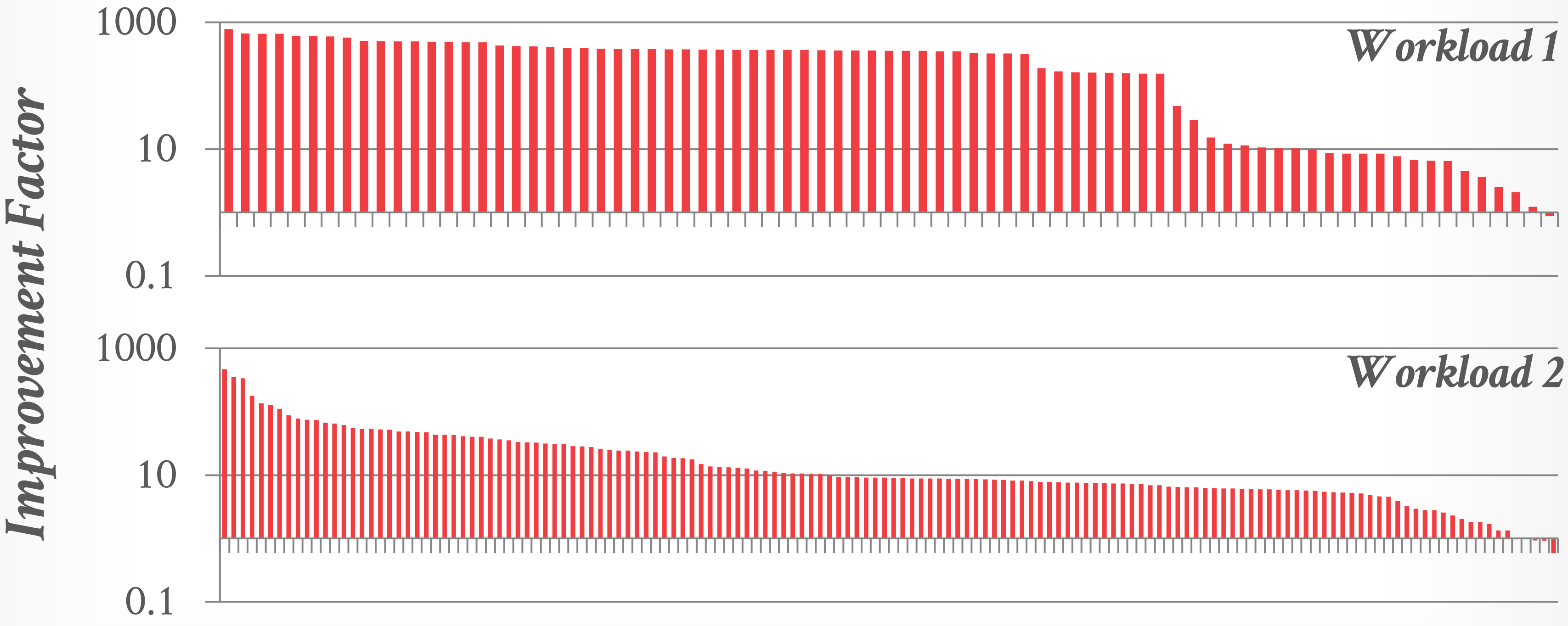
All SQL datatypes.

APPLICABILITY / COVERAGE

	# of Scalar UDFs	*Froid Compatible*	
Workload 1	178	150	**84%**
Workload 2	90	82	**91%**
Workload 3	22	21	**95%**

UDF IMPROVEMENT STUDY

Table: 100k Tuples



Source: Karthik Ramachandra

APFEL: UDFs-TO-CTEs

Rewrite UDFs into plain SQL commands.

Use recursive common table expressions (CTEs) to support iterations and other control flow concepts not supported in Froid.

Implemented as a rewrite middleware layer on top of any DBMS that supports CTEs.

COMPILING PL/SQL AWAY
CIDR 2020

UDFs-TO-CTEs OVERVIEW

Step #1 – Static Single Assignment Form

Step #2 – Administrative Normal Form

Step #3 – Mutual to Direct Recursion

Step #4 – Tail Recursion to **WITH RECURSIVE**

Step #5 – Run Through Query Optimizer

STEP #1 – STATIC SINGLE ASSIGNMENT

```
CREATE FUNCTION pow(x int, n int)
RETURNS int AS
$$
 DECLARE
  i int = 0;
  p int = 1;
 BEGIN
  WHILE i < n LOOP
   p = p * x;
   i = i + 1;
  END LOOP;
  RETURN p;
 END;
$$
```

```
pow(x,n):
        $i_0 \leftarrow 0$;
        $p_0 \leftarrow 0$;
 while: $i_1 \leftarrow \Phi(i_0,i_2)$;
        $p_1 \leftarrow \Phi(p_0,p_2)$;
        if $i_1 < n$ then
          goto loop;
        else
          goto exit;
  loop: $p_2 \leftarrow p_1 * x$;
        $i_2 \leftarrow i_1 + 1$;
        goto while;
  exit: return $p_1$;
```

Source: Torsten Grust

STEP #2 – ADMINISTRATIVE NORMAL FORM

```
pow(x,n):
         $i_0$ ← 0;
         $p_0$ ← 0;
 while:  $i_1$ ← Φ($i_0$,$i_2$);
         $p_1$ ← Φ($p_0$,$p_2$);
         if $i_1$ < n then
           goto loop;
         else
           goto exit;
  loop:  $p_2$ ← $p_1$ * x;
         $i_2$ ← $i_1$ + 1;
         goto while;
  exit:  return $p_1$;
```

```
pow(x,n) =
  let $i_0$ = 0 in
   let $p_0$ = 1 in
     while($i_0$,$p_0$,x,n)

while($i_1$,$p_1$,x,n) =
  let $t_0$ = $i_1$ >= n in
   if $t_0$ then $p_1$
   else body($i_1$,$p_1$,x,n)

body($i_1$,$p_1$,x,n) =
  let $p_2$ = $p_1$ * x in
   let $i_2$ = $i_1$ + 1 in
    while($i_2$,$p_2$,x,n)
```

Source: Torsten Grust

STEP #3 – MUTUAL TO DIRECT RECURSION

```
pow(x,n) =
  let i_0 = 0 in
   let p_0 = 1 in
     while(i_0,p_0,x,n)

while(i_1,p_1,x,n) =
  let t_0 = i_1 >= n in
   if t_0 then p_1
   else body(i_1,p_1,x,n)

body(i_1,p_1,x,n) =
  let p_2 = p_1 * x in
   let i_2 = i_1 + 1 in
    while(i_2,p_2,x,n)
```

```
pow(x,n) =
  let i_0 = 0 in
   let p_0 = 1 in
     run(i_0,p_0,x,n)

run(i_1,p_1,x,n) =
  let t_0 = i_1 >= n in
   if t_0 then p_1
   else
    let p_2 = p_1 * x in
     let i_2 = i_1 + 1 in
      run(i_2,p_2,x,n)
```

Source: Torsten Grust

STEP #4 – WITH RECURSIVE

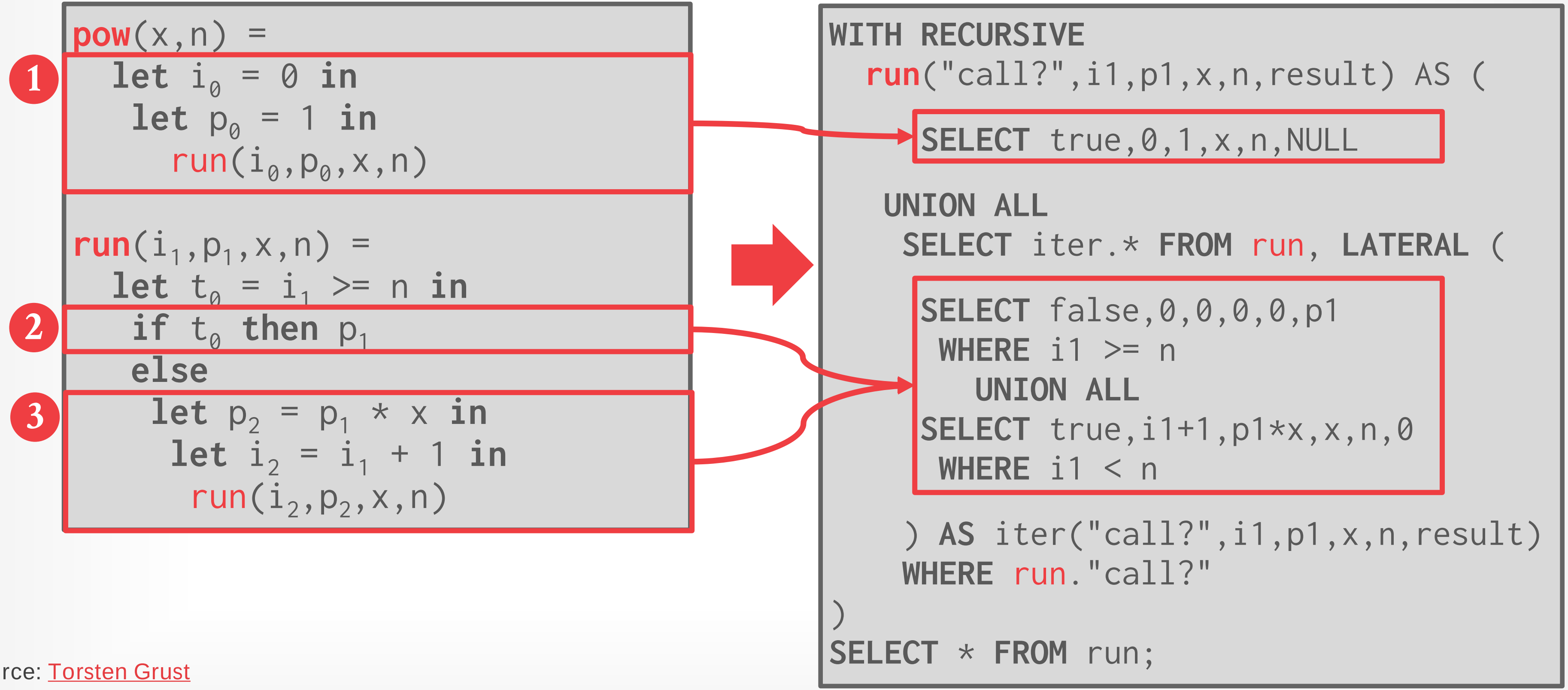
```
pow(x,n) =
  let $i_0$ = 0 in
   let $p_0$ = 1 in
     run($i_0$,$p_0$,x,n)

run($i_1$,$p_1$,x,n) =
  let $t_0$ = $i_1$ >= n in
   if $t_0$ then $p_1$
   else
    let $p_2$ = $p_1$ * x in
     let $i_2$ = $i_1$ + 1 in
      run($i_2$,$p_2$,x,n)
```

```sql
WITH RECURSIVE
  run("call?",i1,p1,x,n,result) AS (

     SELECT true,0,1,x,n,NULL

   UNION ALL
    SELECT iter.* FROM run, LATERAL (

     SELECT false,0,0,0,0,p1
      WHERE i1 >= n
        UNION ALL
     SELECT true,i1+1,p1*x,x,n,0
      WHERE i1 < n

    ) AS iter("call?",i1,p1,x,n,result)
    WHERE run."call?"
)
SELECT * FROM run;
```

Source: Torsten Grust

STEP #4 – WITH RECURSIVE



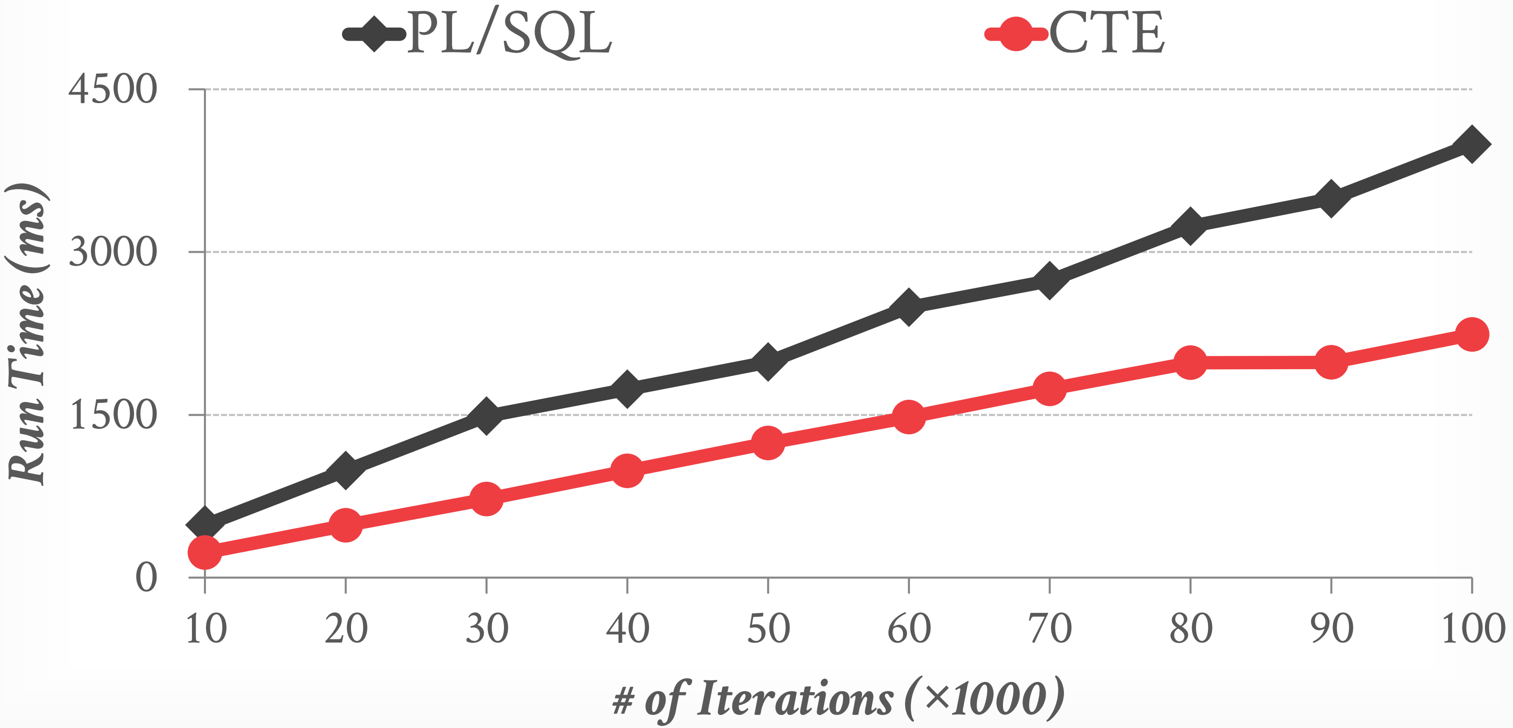
```
pow(x,n) =
1   let i_0 = 0 in
     let p_0 = 1 in
       run(i_0,p_0,x,n)

run(i_1,p_1,x,n) =
   let t_0 = i_1 >= n in
2    if t_0 then p_1
     else
3     let p_2 = p_1 * x in
       let i_2 = i_1 + 1 in
        run(i_2,p_2,x,n)
```

```
WITH RECURSIVE
  run("call?",i1,p1,x,n,result) AS (

     SELECT true,0,1,x,n,NULL

   UNION ALL
    SELECT iter.* FROM run, LATERAL (

     SELECT false,0,0,0,0,p1
      WHERE i1 >= n
        UNION ALL
     SELECT true,i1+1,p1*x,x,n,0
      WHERE i1 < n

    ) AS iter("call?",i1,p1,x,n,result)
    WHERE run."call?"
)
SELECT * FROM run;
```

Source: Torsten Grust

UDFs-TO-CTEs EVALUATION

POW UDF on Postgres v11.3



Source: Torsten Grust

SAM ARCH'S

WHY FROID DOESN'T WORK UNLESS YOU HAVE GERMANS

FROID: WHAT HAPPENED NEXT?

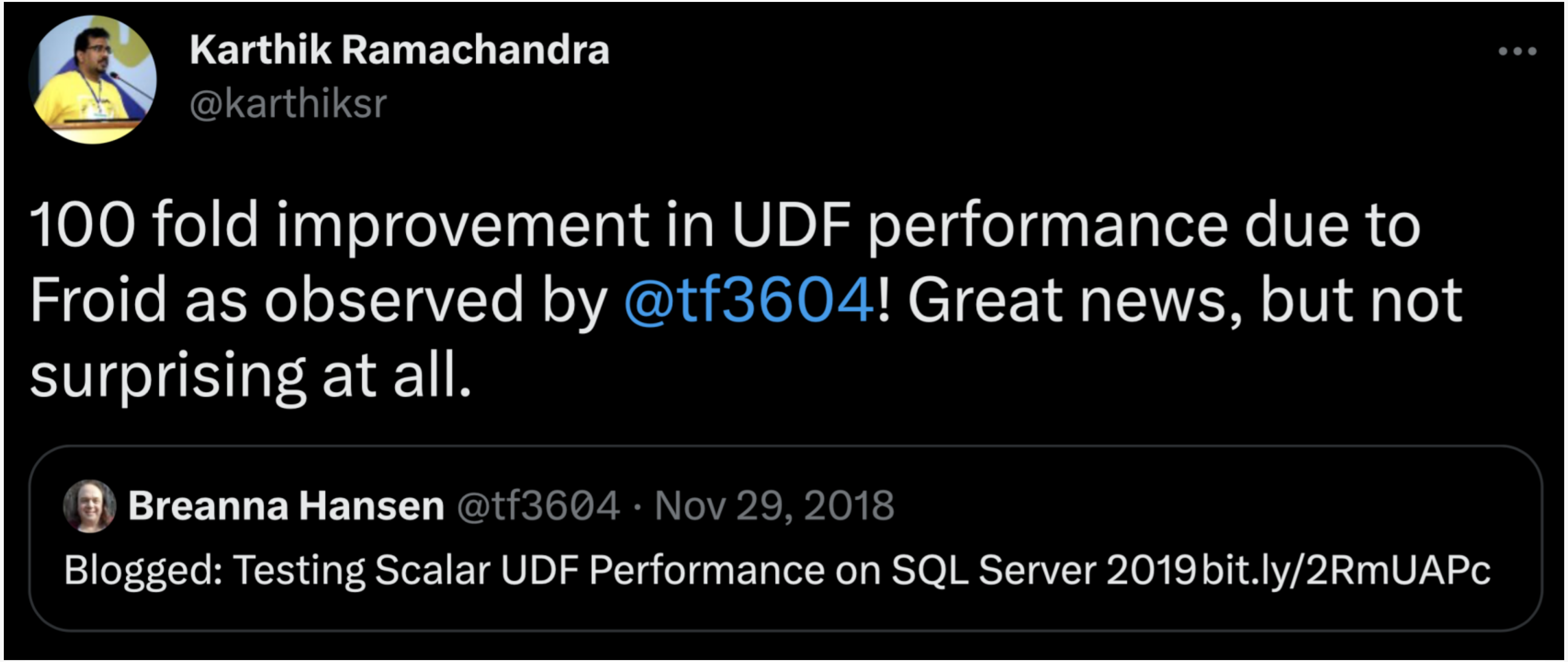
2018 – Froid added to SQL Server 2019.

FROID: WHAT HAPPENED NEXT?

2018 – Froid added to SQL Server 2019.

2019 – Huge performance wins in the wild.

FROID: WHAT HAPPENED NEXT?



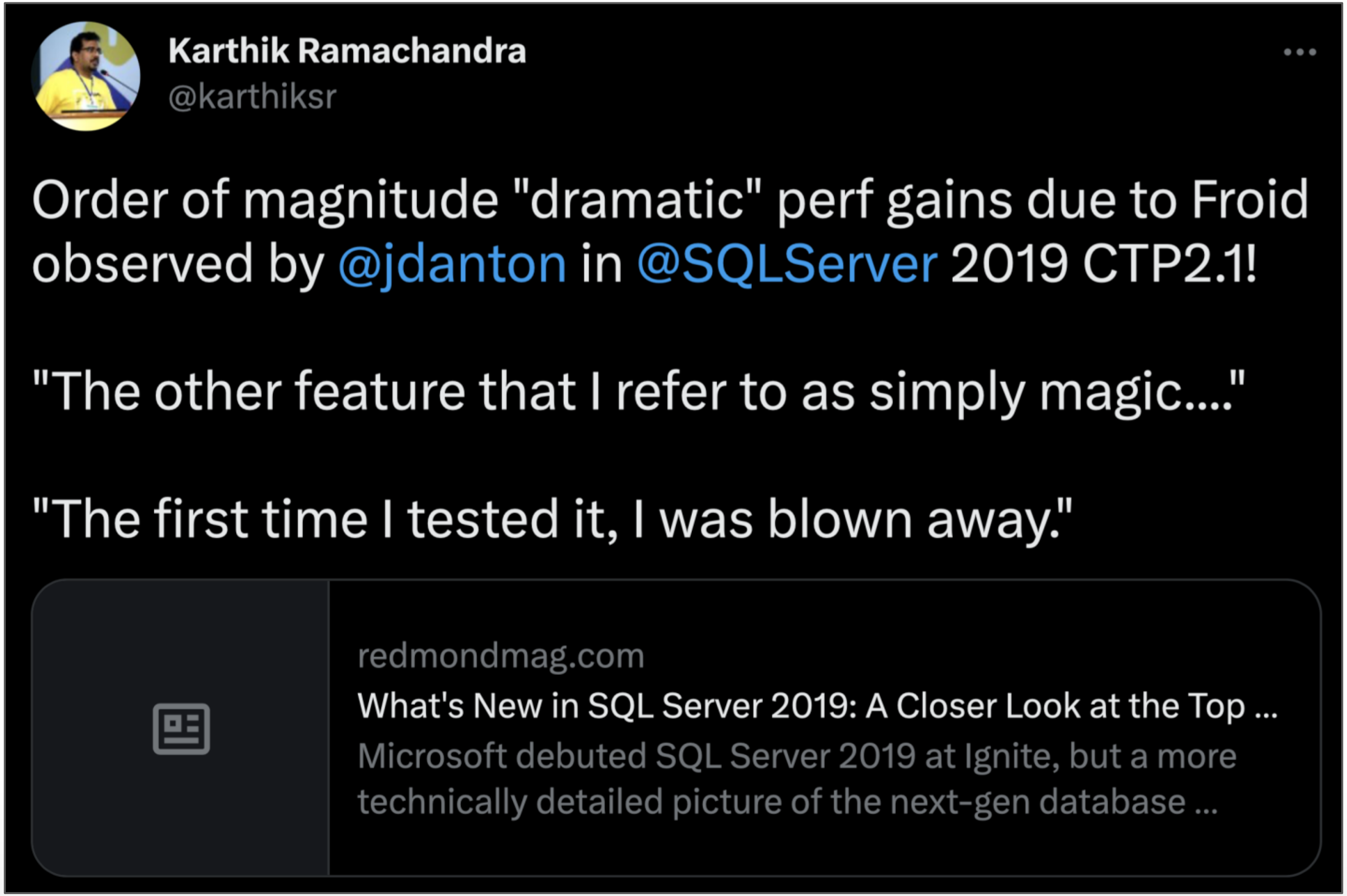
Karthik Ramachandra
@karthiksr

100 fold improvement in UDF performance due to Froid as observed by @tf3604! Great news, but not surprising at all.

Breanna Hansen @tf3604 · Nov 29, 2018

Blogged: Testing Scalar UDF Performance on SQL Server 2019 bit.ly/2RmUAPc

FROID: WHAT HAPPENED NEXT?



Karthik Ramachandra
@karthiksr

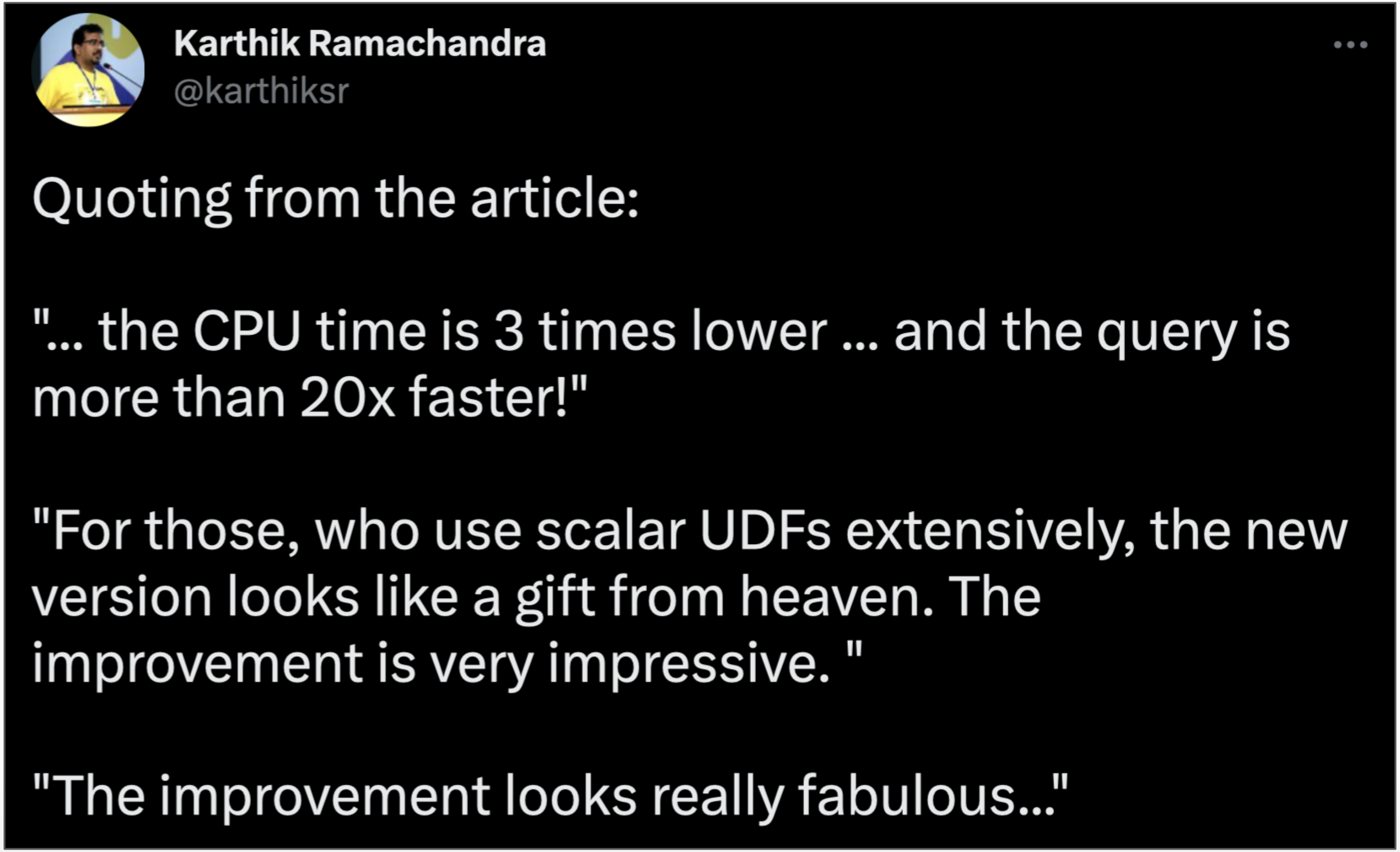
Order of magnitude "dramatic" perf gains due to Froid observed by @jdanton in @SQLServer 2019 CTP2.1!

"The other feature that I refer to as simply magic...."

"The first time I tested it, I was blown away."

redmondmag.com
What's New in SQL Server 2019: A Closer Look at the Top ...
Microsoft debuted SQL Server 2019 at Ignite, but a more technically detailed picture of the next-gen database ...

FROID: WHAT HAPPENED NEXT?



Karthik Ramachandra
@karthiksr

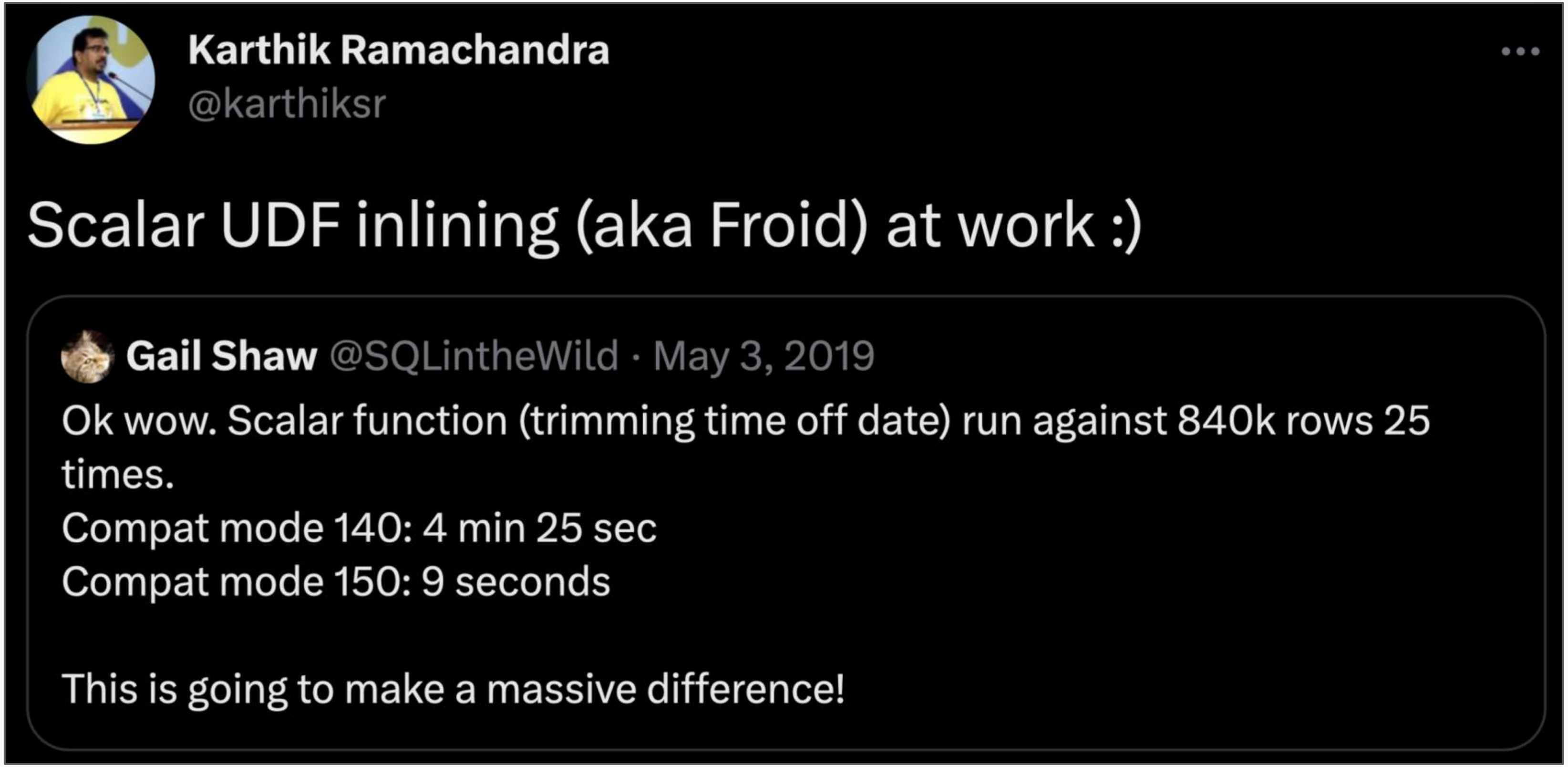
Quoting from the article:

"... the CPU time is 3 times lower ... and the query is more than 20x faster!"

"For those, who use scalar UDFs extensively, the new version looks like a gift from heaven. The improvement is very impressive. "

"The improvement looks really fabulous..."

FROID: WHAT HAPPENED NEXT?



Karthik Ramachandra
@karthiksr

Scalar UDF inlining (aka Froid) at work :)

Gail Shaw @SQLintheWild · May 3, 2019

Ok wow. Scalar function (trimming time off date) run against 840k rows 25 times.
Compat mode 140: 4 min 25 sec
Compat mode 150: 9 seconds

This is going to make a massive difference!

FROID: WHAT HAPPENED NEXT?

2018 – Froid added to SQL Server 2019.

2019 – Huge performance wins in the wild.

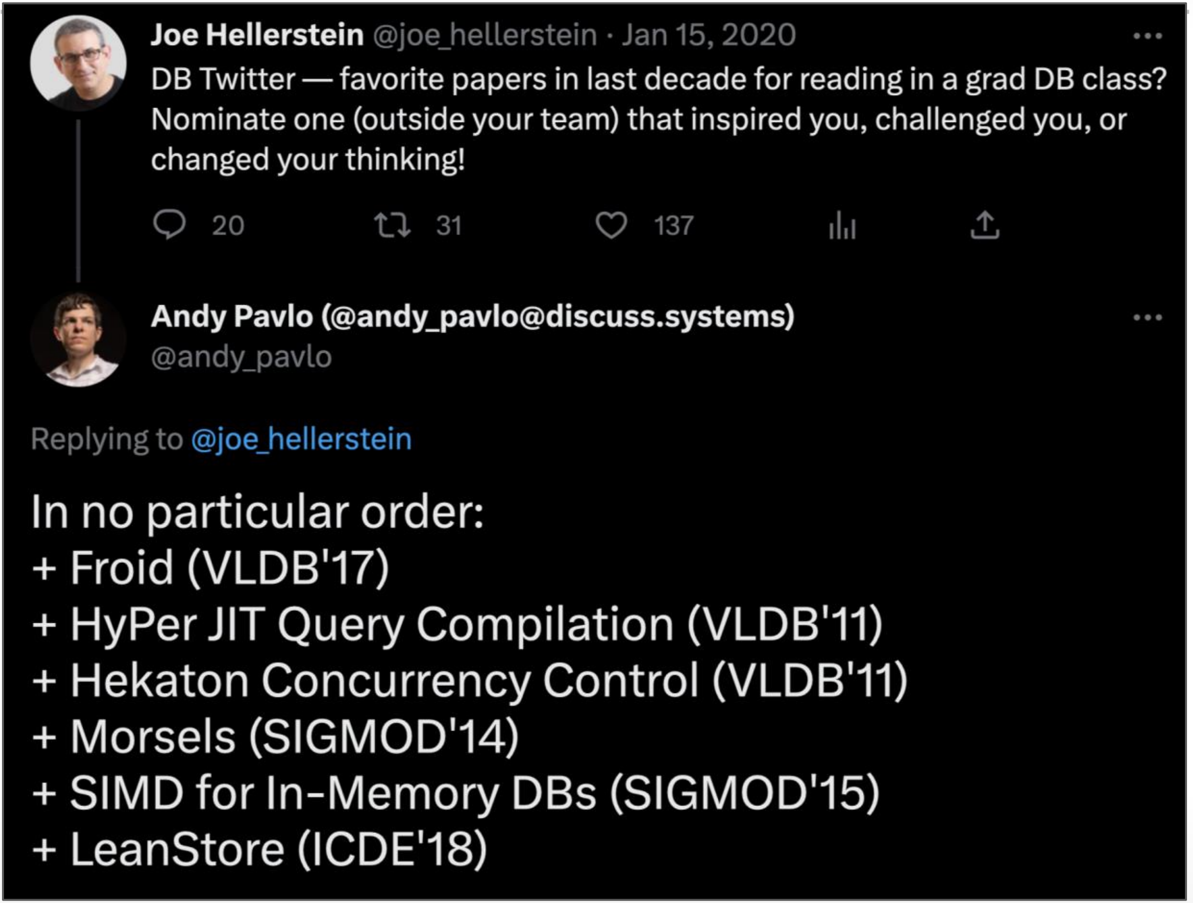
2020 – High praise from Andy.

FROID: WHAT HAPPENED NEXT?

2

2

2



Joe Hellerstein @joe_hellerstein · Jan 15, 2020

DB Twitter — favorite papers in last decade for reading in a grad DB class? Nominate one (outside your team) that inspired you, challenged you, or changed your thinking!

20 31 137

Andy Pavlo (@andy_pavlo@discuss.systems)
@andy_pavlo

Replying to @joe_hellerstein

In no particular order:
+ Froid (VLDB'17)
+ HyPer JIT Query Compilation (VLDB'11)
+ Hekaton Concurrency Control (VLDB'11)
+ Morsels (SIGMOD'14)
+ SIMD for In-Memory DBs (SIGMOD'15)
+ LeanStore (ICDE'18)

FROID: WHAT HAPPENED NEXT?

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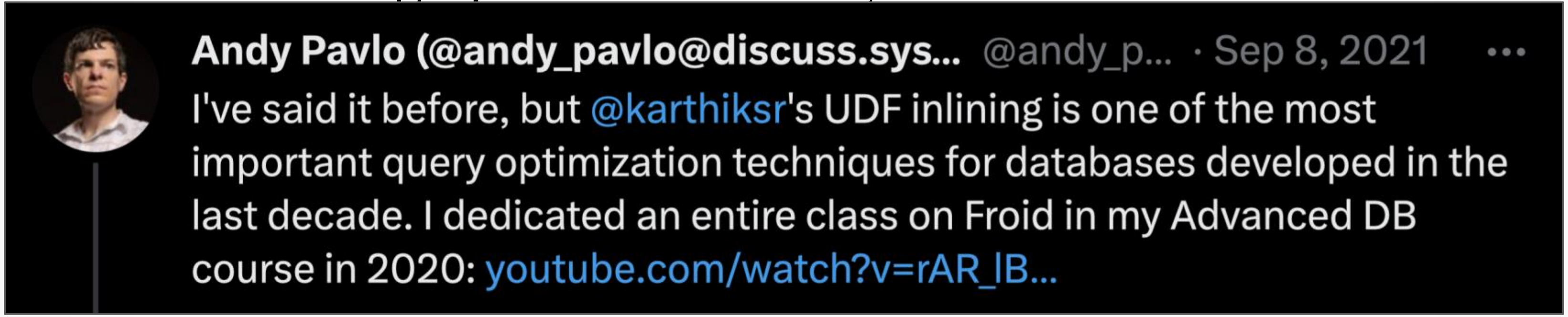


Andy Pavlo (@andy_pavlo@discuss.sys... @andy_p... · Sep 8, 2021

I've said it before, but @karthiksr's UDF inlining is one of the most important query optimization techniques for databases developed in the last decade. I dedicated an entire class on Froid in my Advanced DB course in 2020: youtube.com/watch?v=rAR_lB...

FROID: WHAT HAPPENED NEXT?

2018 – Froid added to SQL Server 2019.

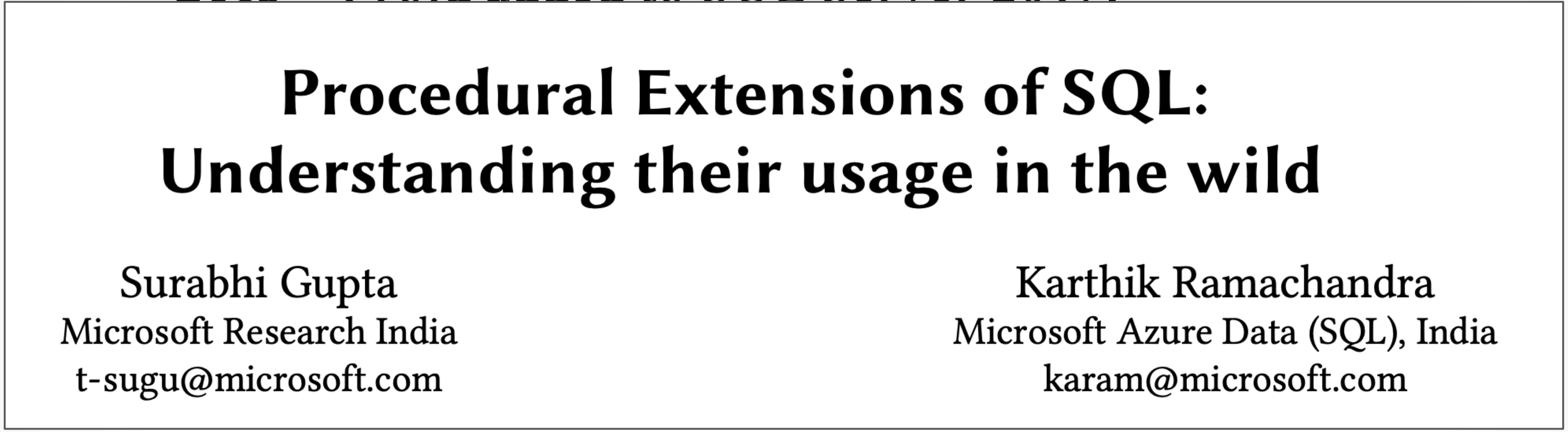
2019 – Huge performance wins in the wild.

2020 – High praise from Andy.

2021 – ProcBench paper released.

FROID: WHAT HAPPENED NEXT?

2018 – Froid added to SQL Server 2019.



Procedural Extensions of SQL: Understanding their usage in the wild

Surabhi Gupta
Microsoft Research India
t-sugu@microsoft.com

Karthik Ramachandra
Microsoft Azure Data (SQL), India
karam@microsoft.com

PROCEDURAL EXTENSIONS OF SQL

Microsoft team published an analysis of real world UDFs, TVFs, Triggers and Stored Procedures.

Also released an open-source benchmark based on their analysis called SQL ProcBench.

- → Authors argue that ProcBench faithfully represents real world workloads

PROCEDURAL EXTENSIONS OF SQL: UNDERSTANDING THEIR USAGE IN THE WILD
VLDB 2021

SCALAR UDFS IN THE PROCBENCH

UDFs with no parameters

```
SELECT maxReturnReasonWeb();
```

```
CREATE FUNCTION maxReturnReasonWeb()
RETURNS char(100) AS
BEGIN
 DECLARE @reason_desc char(100);

 SELECT @reason_desc
   FROM …;

 RETURN @reason_desc;
END
```

UDF invoked once

No substantial performance advantage with UDF Inlining

SCALAR UDFS IN THE PROCBENCH

UDFs with parameters

```
CREATE FUNCTION cust_level(@ckey int)
RETURNS char(10) AS
BEGIN
 DECLARE @total float;
 DECLARE @level char(10);

 SELECT @total = SUM(o_totalprice)
   FROM orders WHERE o_custkey=@ckey;

 IF (@total > 1000000)
  SET @level = 'Platinum';
 ELSE
  SET @level = 'Regular';

 RETURN @level;
END
```

```
SELECT cust_level(customer_id)
  FROM customer;
```

UDF invoked per customer

Implicit join between tables

Huge performance win with UDF Inlining by “decorrelating” the subquery

HOW DOES FROID FARE?

FROID is supported in SQL Server 2019

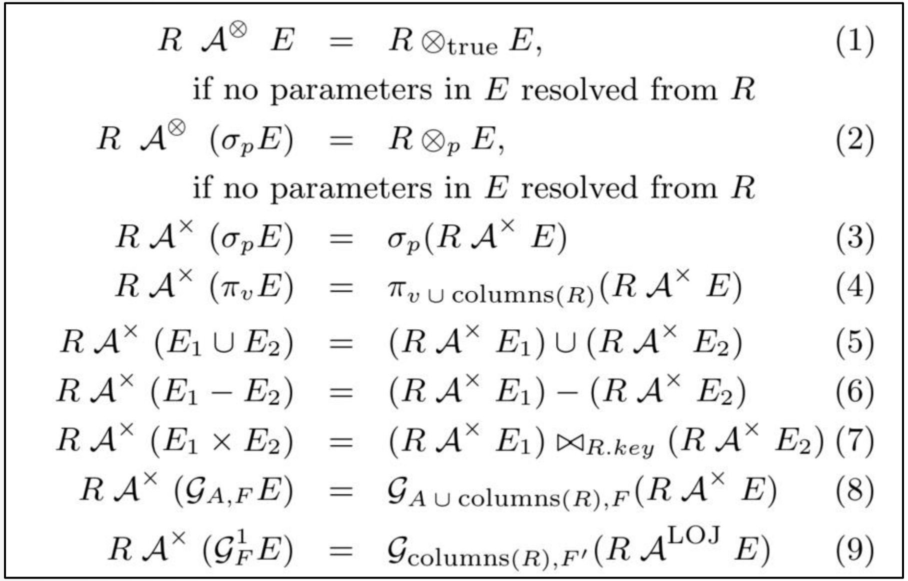
We tested SQL Server 2019 on the ProcBench

SQL Server's optimizer could only decorrelate **two out of 13** of the UDFs with parameters

The German's Umbra optimizer could decorrelate **all** 13 UDFs.

DECORRELATION OF SUBQUERIES (MSSQL)

Algebraic rewrite rules for APPLY



$$R\ \mathcal{A}^{\otimes}\ E = R \otimes_{\text{true}} E, \tag{1}$$

if no parameters in E resolved from R

$$R\ \mathcal{A}^{\otimes}\ (\sigma_p E) = R \otimes_p E, \tag{2}$$

if no parameters in E resolved from R

$$R\ \mathcal{A}^{\times}\ (\sigma_p E) = \sigma_p(R\ \mathcal{A}^{\times}\ E) \tag{3}$$

$$R\ \mathcal{A}^{\times}\ (\pi_v E) = \pi_{v \cup \text{columns}(R)}(R\ \mathcal{A}^{\times}\ E) \tag{4}$$

$$R\ \mathcal{A}^{\times}\ (E_1 \cup E_2) = (R\ \mathcal{A}^{\times}\ E_1) \cup (R\ \mathcal{A}^{\times}\ E_2) \tag{5}$$

$$R\ \mathcal{A}^{\times}\ (E_1 - E_2) = (R\ \mathcal{A}^{\times}\ E_1) - (R\ \mathcal{A}^{\times}\ E_2) \tag{6}$$

$$R\ \mathcal{A}^{\times}\ (E_1 \times E_2) = (R\ \mathcal{A}^{\times}\ E_1) \bowtie_{R.key} (R\ \mathcal{A}^{\times}\ E_2) \tag{7}$$

$$R\ \mathcal{A}^{\times}\ (\mathcal{G}_{A,F} E) = \mathcal{G}_{A \cup \text{columns}(R),F}(R\ \mathcal{A}^{\times}\ E) \tag{8}$$

$$R\ \mathcal{A}^{\times}\ (\mathcal{G}^1_F E) = \mathcal{G}_{\text{columns}(R),F'}(R\ \mathcal{A}^{\text{LOJ}}\ E) \tag{9}$$

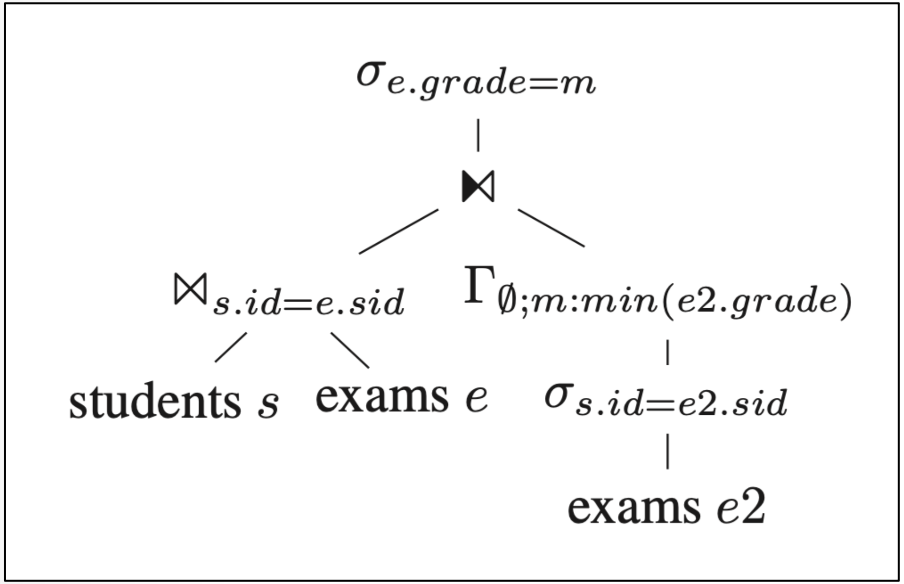
Execute the rewrite rules where applicable

Some rewrites may require duplicating subexpressions in the query plan tree (and are cost-based decisions)

ORTHOGONAL OPTIMIZATION OF SUBQUERIES AND AGGREGATION
SIGMOD 2001

DECORRELATION OF SUBQUERIES (GERMANS)

Dependent Join Operator



Introduces a new "Dependent Join" operator into the Query Plan DAG

Systematically decorrelates any subquery

UNNESTING ARBITRARY QUERIES
BTW 2015

IMPLICATIONS FOR UDF INLINING

UDF Inlining is amazing. But to achieve great performance from UDF Inlining requires a German-style query optimizer.

→ SQL Server's optimizer is good (according to Andy) but not as good as the Germans for this task.

This is why we are extending DuckDB to support UDFs

PARTING THOUGHTS

This is huge. You rarely get 500x speed up without either switching to a new DBMS or rewriting your application.

Another optimization approach is to compile the UDF into machine code.

→ This does not solve the optimizer's cost model problem.

NEXT CLASS

Database Networking Protocols