Lecture 24: Server-side Logic Execution

CREATING THE NEXT®

Today's Agenda

Recap

Adaptive Query Optimization

- The "plan-first execute-second" approach to query planning is notoriously error prone.
- Optimizers should work with the execution engine to provide alternative plan strategies and receive feedback.
- Adaptive techniques now appear in many of the major commercial DBMSs
  - DB2, Oracle, MSSQL, TeraData
- Approaches
  - Approach 1: Modify Future Invocations
  - Approach 2: Replan Current Invocation
  - Approach 3: Plan Pivot Points

Cost Models

- Using number of tuples processed is a reasonable cost model for in-memory DBMSs.
  - But computing this is non-trivial.
  - A combination of sampling + sketches allows the DBMS to achieve accurate estimations.

Observation

- Until now, we have assumed that all of the logic for an application is located in the application itself.
- The application has a "conversation" with the DBMS to store/retrieve data.
  - **Protocols:** JDBC, ODBC

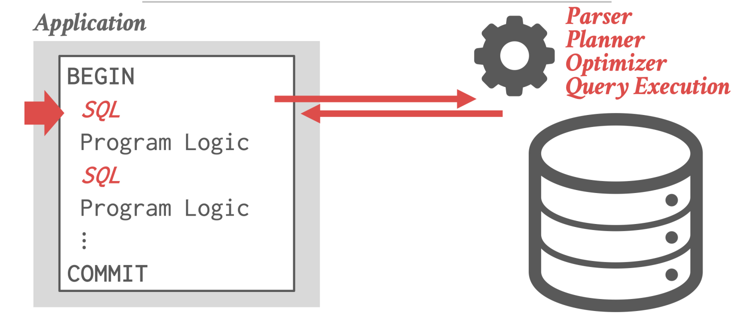
Today's Agenda

- Background
- UDF In-lining
- UDF to CTE Conversion

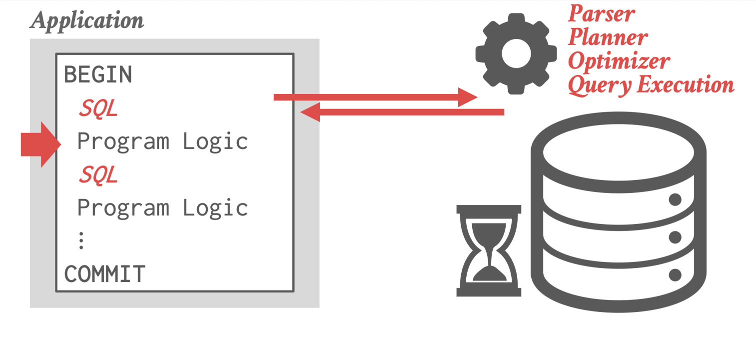
Background

Conversational Database API

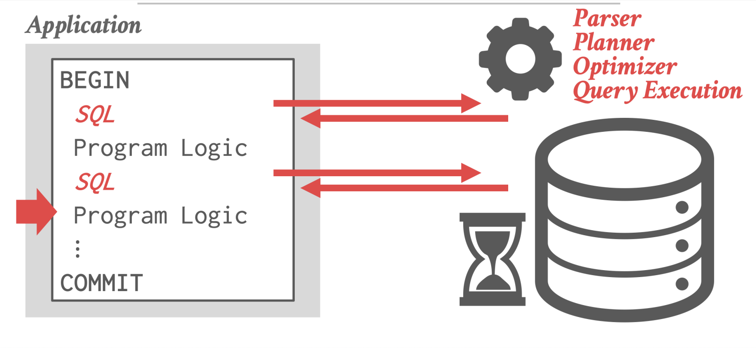
Conversational Database API



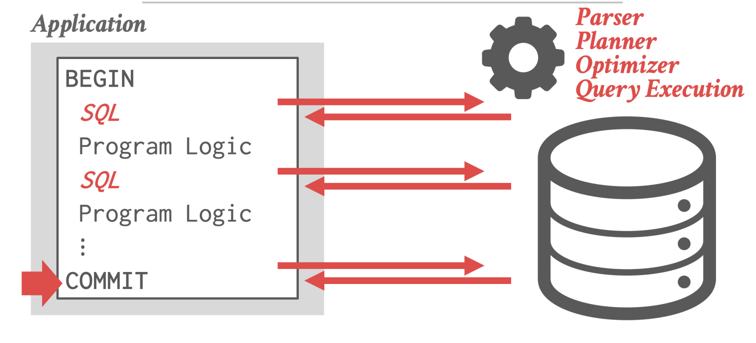
Conversational Database API



Conversational Database API



Conversational Database API



Conversational Database API

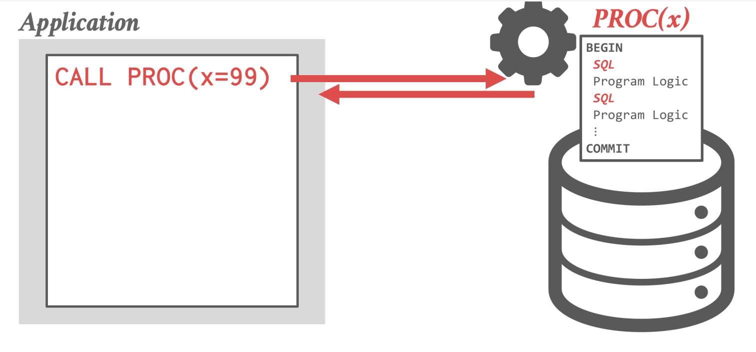
- The application has a "conversation" with the DBMS to store/retrieve data.
- Locks are held for the duration of the transaction
- Multiple network round-trips

Embedded Database Logic

- Move application logic into the DBMS to avoid multiple network round-trips and to extend the functionality of the DBMS.
- Potential Benefits
  - Efficiency
  - Reuse logic across web and mobile applications

Embedded Database Logic: Stored Procedures

Embedded Database Logic: Stored Procedures



Embedded Database Logic

- Stored Procedures (may contain DML statements, call UDFs *e.t.c.*)
- User-Defined Functions (UDFs)
- Triggers
- User-Defined Types (UDTs)
- User-Defined Aggregates (UDAs)

User-Defined Functions

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)
- **Examples:** PL/SQL, plPG/SQL

UDF Example

- 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
```

```
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
```

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 UDFs as black boxes.
  - Unable to estimate cost if you don't know what a UDF is going to do when you run it.
- 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

```
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        --- User Defined Function
GROUP BY l_shipmode ORDER BY l_shipmode
```

UDF Performance

```
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
```

UDF Performance

- Microsoft SQL Server
- TPC-H Q12 using a UDF (Scale Factor=1).
- Reference
  - Original Query: 0.8 sec
  - Query + UDF: 13 hr 30 min

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.
- 2015 – Froid project begins @ MSFT Gray Lab.
- 2018 – Froid added to SQL Server 2019.

UDF In-lining

Froid: UDF In-lining

- Automatically convert UDFs into relational 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.
- Reference

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 – De-correlate

```
SELECT name FROM sailors AS S
 WHERE EXISTS (
    SELECT * FROM reserves AS R
     WHERE S.sid = R.sid
       AND R.day = '2020-04-22'
 )
```

```
SELECT name
  FROM sailors AS S, reserves AS R
 WHERE S.sid = R.sid
   AND R.day = '2020-04-22'
```

Lateral Join

- Subqueries appearing in FROM can be preceded by the key word LATERAL.
- This allows them to reference columns provided by preceding FROM items.
- Without LATERAL, each subquery is evaluated independently and so cannot cross-reference any other FROM item.
- LATERAL is primarily useful when the cross-referenced column is necessary for computing the row(s) to be joined.

Lateral Join

```
CREATE TABLE orders (
  id SERIAL PRIMARY KEY,  user_id INT,  created TIMESTAMP
);
--- Query
SELECT user_id, first_order, next_order, id FROM
(SELECT user_id, min(created) AS first_order FROM orders GROUP BY user_id) 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)
   o2 ON true LIMIT 1;
```

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 Through Query 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;`

Step 2 – Break UDF 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
```

Regions: 1 = DECLARE … SELECT @total …; 2 = SET @level = 'Platinum'; 3 = SET @level = 'Regular'; 4 = 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
```

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 UDF Expression into Query

Original Query

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

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

Step 5 - Run Through Query Optimizer

```
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;
```

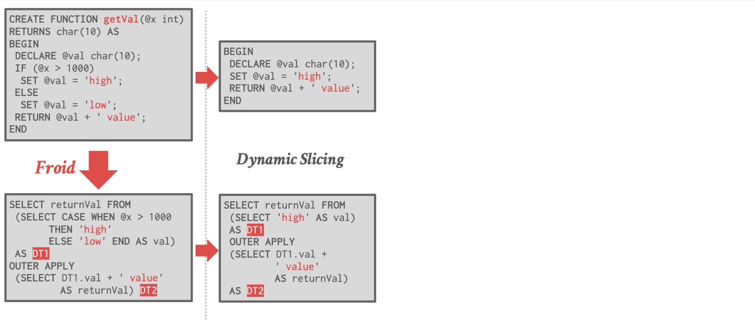
```
SELECT c.c_custkey,
        CASE WHEN e.total > 1000000
             THEN 'Platinum'
             ELSE 'Regular'
        END
  FROM customer c LEFT OUTER JOIN
     (SELECT o_custkey,
               SUM(o_totalprice) AS total
          FROM order GROUP BY o_custkey
      ) AS e
    ON c.c_custkey=e.o_custkey;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

Bonus Optimizations

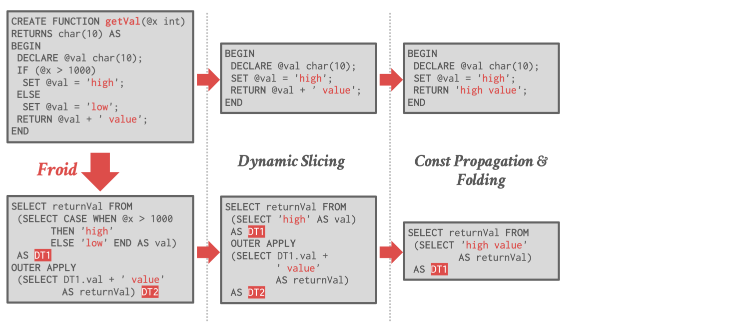
```
CREATE FUNCTION getVal(@x int)
RETURNS char(10) AS
BEGIN
 DECLARE @val char(10);
 IF (@x > 1000)
  SET @val = 'high';
 ELSE
  SET @val = 'low';
 RETURN @val + ' value';
END
```

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

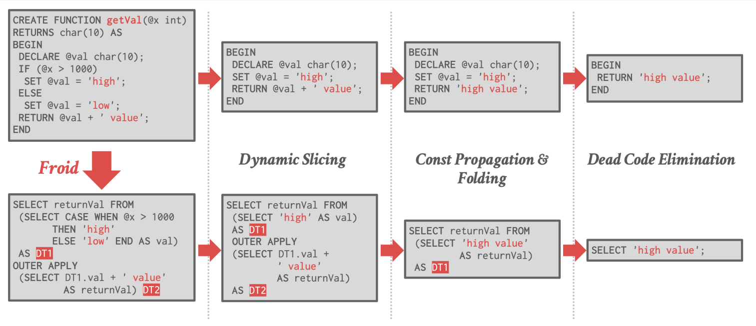
Bonus Optimizations



Bonus Optimizations



Bonus Optimizations



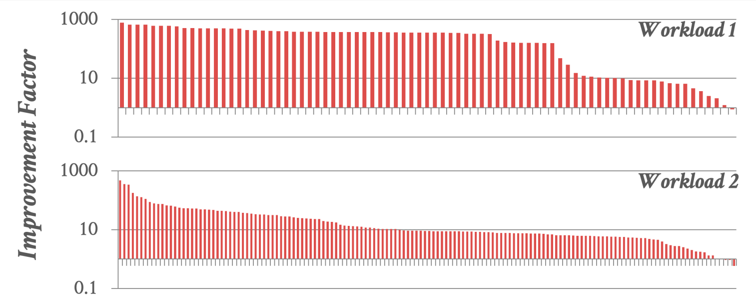
Supported Operations (2019)

- T-SQL Syntax:
  - *DECLARE*, *SET* (variable declaration, assignment)
  - *SELECT* (SQL query, assignment)
  - *IF* / *ELSE* / *ELSEIF* (arbitrary nesting)
  - *RETURN* (multiple occurrences)
  - *EXISTS*, *NOTEXISTS*, *ISNULL*, *IN*, . . . (Other relational algebra operations)
- UDF invocation (nested/recursive with configurable depth)
- All SQL datatypes.
- Limitations: Loops, Dynamic Queries, Exceptions

Applicability / Coverage

Workloads	Number of Scalar UDFs	Froid Compatible
Workload 1	178	150
Workload 2	90	82
Workload 3	22	21

UDF Improvement Study



UDFs to CTEs Conversion

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.
- DBMS Agnostic
  - Can be implemented as a rewrite middleware layer on top of any DBMS that supports CTEs.
- Reference

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 Form

```
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):
        i0 ← 0;
        p0 ← 0;
 while: i1 ← Φ(i0,i2);
        p1 ← Φ(p0,p2);
        if i1 < n then
          goto loop;
        else
          goto exit;
  loop: p2 ← p1 * x;
        i2 ← i1 + 1;
        goto while;
  exit: return p1;
```

Step 2 – Administrative Normal Form

```
pow(x,n):
        i₀ ← 0;
        p₀ ← 0;
 while: i₁ ← Φ(i₀,i₂);
        p₁ ← Φ(p₀,p₂);
        if i₁ < n then
          goto loop;
        else
          goto exit;
  loop: p₂ ← p₁ * x;
        i₂ ← i₁ + 1;
        goto while;
  exit: return p₁;
```

⇒

```
pow(x,n) =
  let i₀ = 0 in
   let p₀ = 1 in
     while(i₀,p₀,x,n)

while(i₁,p₁,x,n) =
  let t₀ = i₁ >= n in
   if t₀ then p₁
   else body(i₁,p₁,x,n)

body(i₁,p₁,x,n) =
  let p₂ = p₁ * x in
   let i₂ = i₁ + 1 in
    while(i₂,p₂,x,n)
```

Step 3 – Mutual to Direct Recursion

```
pow(x,n) =
  let i0 = 0 in
   let p0 = 1 in
     while(i0,p0,x,n)

while(i1,p1,x,n) =
  let t0 = i1 >= n in
   if t0 then p1
   else body(i1,p1,x,n)

body(i1,p1,x,n) =
  let p2 = p1 * x in
   let i2 = i1 + 1 in
    while(i2,p2,x,n)
```

→

```
pow(x,n) =
  let i0 = 0 in
   let p0 = 1 in
     run(i0,p0,x,n)

run(i1,p1,x,n) =
  let t0 = i1 >= n in
   if t0 then p1
   else
    let p2 = p1 * x in
     let i2 = i1 + 1 in
      run(i2,p2,x,n)
```

Step 4 – WITH RECURSIVE

```
pow(x,n) =
  let i0 = 0 in            (1)
   let p0 = 1 in
     run(i0,p0,x,n)

run(i1,p1,x,n) =
  let t0 = i1 >= n in
   if t0 then p1           (2)
   else
    let p2 = p1 * x in     (3)
     let i2 = i1 + 1 in
      run(i2,p2,x,n)
```

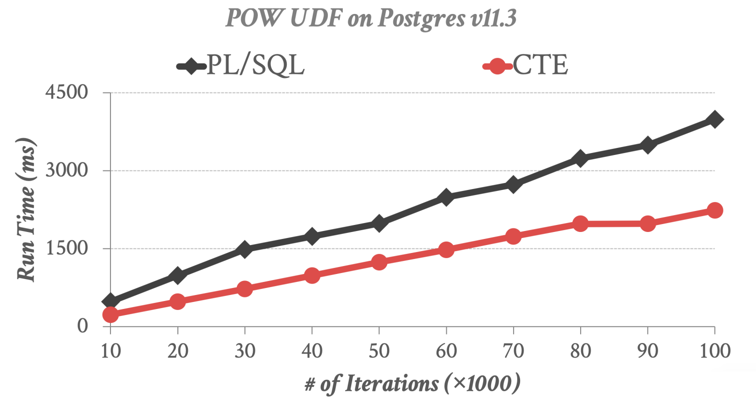
```
WITH RECURSIVE
  run("call?",i1,p1,x,n,result) AS (

      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;
```

UDFs-to-CTEs Evaluation



Summary

- This is huge. You rarely get 500$\times$ 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.

Retrospective

Lessons learned

- Let's take a step back and think about what happened
- Systems programming is both hard **and** rewarding
- Become a better programmer through the study of database systems internals
- Going forth, you should have a good understanding how systems work

Big Ideas

- Database systems are awesome – but are not magic.
- Elegant abstractions are magic.
- Declarativity enables usability and performance.
- Building systems software is more than hacking
- There are recurring motifs in systems programming.
- CS has an intellectual history and you can contribute.

What Next?

- We have covered the entire stack of systems programming
  - Storage Management (Part 1)
  - Access Methods (Part 1)
  - Query Execution (Part 1)
  - Logging and Recovery Methods (Part 2)
  - Concurrency Control (Part 2)
  - Query Optimization (Part 2)
- Stay in touch
  - Tell me when this course helps you out with future courses (or jobs!)
  - Ask me cool DBMS questions

Parting Thoughts

- You have surmounted several challenges in this course.
- You make it all worthwhile.
- Please share your feedback via CIOS.
- Go forth and spread the gospel of data systems!

Next Class

- Project Presentations