Advanced SQL

07 — Procedural SQL

Summer 2020

Torsten Grust
Universität Tübingen, Germany

1 ┆ Scripting Language + SQL = Procedural SQL

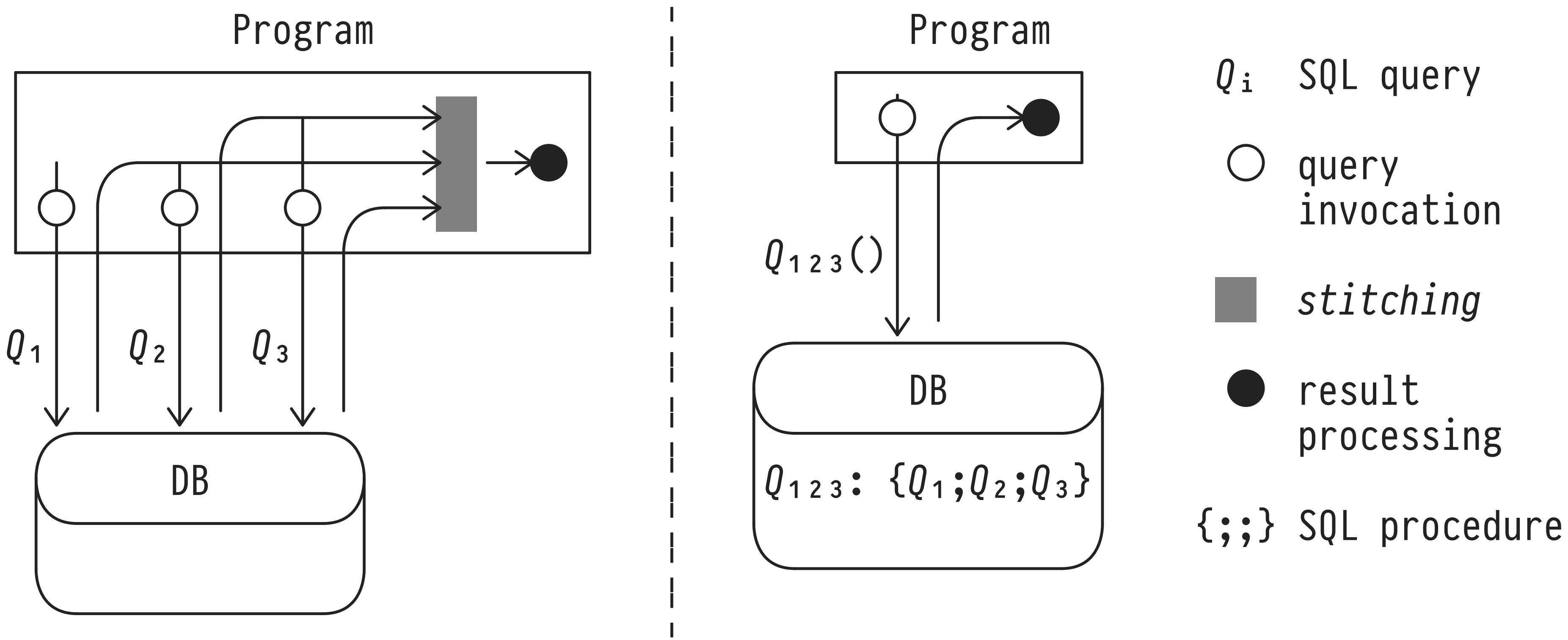
We started out in this course with the aim to **move more computation close to the data.** Admitting recursion in SQL is one way to declaratively express complex computation.

Procedural SQL follows an entirely different path towards this goal:

- Implement application logic *inside* the RDBMS, even if this **computation is inherently procedural** (≡ sequential, imperative).

- Use **SQL as a sub-language of a scripting language** whose types match those of the tabular data model.

Procedural SQL: Less Round-Trips, Less Stitching



- *Stitching*: On the PL heap, piece together the tabular results delivered by the individual SQL queries Q_i.

Procedural SQL aka *Stored Procedures*

Code in Procedural SQL is organized in **functions/procedures that are stored persistently** by the DBMS.[1]

These functions/procedures…

- may be used anywhere that SQL's built-ins could be used,
- inherit all user-defined types, functions, and operators,
- can define new operators, aggregate/window functions, and triggers.

[1] This implies that we need to manage these procedures using familiar constructs like `CREATE PROCEDURE …`, `CREATE FUNCTION …`, `DROP PROCEDURE [IF EXISTS] …`, etc.

PL/SQL:[2] Scripting with SQL Types

```
CREATE FUNCTION f(x_1 τ_1, …, x_n τ_n) RETURNS τ AS
$$ … ‹block› … $$
LANGUAGE PLPGSQL;
```

- The τ_i, τ may be any scalar, array, or (named) row type.
- Limited polymorphism: functions may accept/return types anyelement, anyarray (recall our discussion of SQL UDFs).
    - Functions may return type record (then the caller must provide column names/types through explicit aliasing).
- Functions may return—but *not* accept 😢—sets of (row) values with $\tau \equiv$ SETOF $\bar{\tau}$.

[2] *PL/SQL* is the widely adopted abbreviation for *Procedural Language for SQL*, originating in the Oracle® RDBMS. Variants include *Transact-SQL* (Microsoft® SQL Server) and *PL/pgSQL* (PostgreSQL).

2 ¦ Block Structure

PL/SQL code is organized in (nested) **blocks** that group statements and define **variable scopes:**

```
block { [ DECLARE ‹declarations› ]
        BEGIN
          ‹statement›              -- ◀ any statement may be
        END;                       --    a (sub-)block again
```

- Declared variables are in scope in the block and its sub-blocks. Local names shadow outer names.
- Optionally introduce block with `<< ‹label› >>`: variable *v* may then also be referred to as `‹label›.v`.
- Outermost block of body for *f* has implicit `<< ‹f› >>`.

Block Structure and Variable Scope[3]

in scope	
	CREATE FUNCTION $f(x_1\ \tau_1)$ **RETURNS** τ **AS**
	`$$`
$f.x_1$	`<< o >>` -- outer block
	DECLARE $v\ \tau_v$;
$f.x_1$, $o.v$	**BEGIN**
	⋮
	`<< i >>` -- inner (sub-)block
	DECLARE $v\ \tau_u$;
$f.x_1$, $o.v$, $i.v$	**BEGIN**
	⋮
	END;
	⋮
	END;
	`$$` **LANGUAGE** PLPGSQL;

[3] Additional special variables (like FOUND) are bound in the outermost *f* scope (see below).

3 ┆ Variable Declarations

The optional DECLARE ‹*declarations*› brings **typed variable(s)** *v* into scope. An initial binding expression *e* may be given:

```
DECLARE v [ CONSTANT ] τ [ NOT NULL ] [ := e ];
        ⋮
```

- If := *e* is omitted, *v* has initial value NULL.
- NOT NULL: any assignment of NULL yields a runtime error.
- CONSTANT: the initial binding may not be overwritten.

- Use *c*%TYPE for τ to declare *v* with the same type as variable or table column named *v*.

Variables With Row Types Have Row Values

Let T be a table with **row type** $(c_1\ \tau_1,\ \ldots,\ c_n\ \tau_n)$. Recall: this row type is also known as T. Thus:

```
--                             ▼ row type name
CREATE FUNCTION accessᵢ(t T) RETURNS T.cᵢ%TYPE AS
$$
--          ▼+▼ table + column name
DECLARE x T.cᵢ%TYPE;  -- x has type τᵢ
BEGIN
  x := t.cᵢ;          -- field access uses dot notation
  RETURN x;
END;
$$
LANGUAGE PLPGSQL;
```

4 ┆ PL/SQL Expressions

In PL/SQL, any expression e that could also occur in a SELECT clause, is a valid expression.

In fact, the execution of PL/pgSQL statements like

```
v := e
IF e THEN … ELSE … END IF
```

lead to the evaluation of SELECT e by the SQL interpreter.

- Interoperability between PL/pgSQL and SQL. 👍
- Performance impact: context switches PL/SQL↔SQL. 👎
- If $e \equiv e(x,y)$, compile SQL once with parameters x,y.

5 ┆ PL/SQL Statements — Assignment

```
v := e
```

1. Evaluate e, yields a single value (scalar, row, array, user-defined, including NULL). e may **not be table-valued.**

2. Cast value to type τ of v.
   - SQL casting rules apply (may fail at runtime).
   - e may use textual literal syntax (e.g., for user-defined enumerations, JSON, or geometric objects).

3. Bind variable v to value.

Assignment of Single-Row Query Results

A single-row[4] SQL query augmented with INTO is a valid PL/SQL assignment statement:

❶	❷
SELECT e_1, e_2, …, e_n **INTO** v **FROM** …	**SELECT** e_1, e_2, …, e_n **INTO** v_1, v_2, …, v_n **FROM** …

1. Evaluate SQL query, obtain a single row of n values.
   ❶ Assign row value to row-typed variable v, or
   ❷ assign value of e_i to v_i ($i \in \{1,\ldots,n\}$).

2. Variable FOUND :: boolean indicates if a row was found.

[4] Use INTO STRICT to enforce a single-row query result. Otherwise, the "first" row is picked… 🙈

Assignment of Scalar Query Results

RHS of assignment v := e is evaluated like a regular SQL query. In particular, e may be a *scalar subquery* in (…):

```
v := (Q)    --
            -- Q yields single row, single column: c
            --
```

- Evaluates SELECT (Q) behind the scenes[5]. Thus:
  - assigns cell value c cast to type τ of v, or
  - assigns NULL :: τ to v if Q returns no row, or
  - yields runtime error if Q returns more than one row or column (or if the cast fails). ⚠️

[5] **NB.** Scalar assignment does not update variable FOUND (unlike the INTO construct, see above).

6 ┆ If All You Want Are the Side Effects…

1. Statement `NULL` does nothing (no side effects).

2. SQL **DML statements** (`INSERT`/`DELETE`/`UPDATE`) without `RETURNING` clauses are valid PL/SQL statements: no value is returned, the effect on the database is performed.

3. A SQL **query** `SELECT` …*‹query›*… may be performed solely for its side effects (e.g., invocation of a side-effecting UDF) as well:

```
PERFORM …‹query›… -- ⚠ PERFORM replaces the SELECT keyword
```

Resulting rows are discarded (but variable `FOUND` is set).

7 ¦ Returning From a Non-Table Function (RETURNS τ)

```
RETURN e
```

1. Evaluate *e*, cast value to return type τ of the function.
   - If τ ≡ void, omit *e*. A void function whose control flow reaches the end of the top-level block, returns automatically.
2. Execution resumes in the calling function or query which receives the returned value.

To return multiple values, declare the function to return a row type.

“Returning” From a Table Function (RETURNS SETOF τ)

❶ RETURN NEXT *e*; *s*	❷ RETURN QUERY *Q*; *s*

- **Add (bag semantics: ⊎) to the result table** computed by the function. Execution resumes with following statement *s* — **no** return to the caller yet.
  ❶ Evaluate expression *e*, add scalar/row to result.
  ❷ Evaluate SQL query *Q*, append all rows to result.

- Use plain RETURN; to return the result table accumulated so far and resume execution in the caller.

8 ┆ Conditional Statements

$$\mathbf{IF}\ p_0\ \mathbf{THEN}\ s_0\ \underbrace{[\ \mathbf{ELSIF}\ p_i\ \mathbf{THEN}\ s_i\ ]^*}_{\text{optional, repeatable}}\ \underbrace{[\ \mathbf{ELSE}\ s_e\ ]}_{\text{optional}}\ \mathbf{END\ IF}$$

- Semantics as expected; p_i :: bool, s_i statements.

$$\mathbf{CASE}\ e\ \underbrace{[\ \mathbf{WHEN}\ e_{i1}\ [,\ e_{ij}]^*\ \mathbf{THEN}\ s_i\ ]^+}_{\text{mandatory, repeatable}}\ [\ \mathbf{ELSE}\ s_e\ ]\ \mathbf{END\ CASE}$$

- Execute first branch s_i with $\exists_j\colon e = e_{ij}$.
- Raise CASE_NOT_FOUND exception (see below) if no branch was found and ELSE s_e is missing.

9 Iterated Statements

```
1                                                LOOP s↻ END LOOP
2                                        WHILE p LOOP s↻ END LOOP
3 FOR vᵢ IN [ REVERSE ] e₀..e₁ [ BY e₂ ] LOOP s↻ END LOOP
4                                   FOR vᵣ IN q LOOP s↻ END LOOP
5 FOREACH vₐ IN [ SLICE n ] ARRAY eₐ LOOP s↻ END LOOP
```

1. Endless loop (see EXIT below).
2. p :: bool.
3. $e_{0,1,2}$ :: int. No BY: $e_2 \equiv 1$. v_i :: int (auto-declared) bound to e_0, $e_0 \pm 1{\times}e_2$, $e_0 \pm 2{\times}e_2$, … (REVERSE: $\pm \equiv -$).
4. q SQL query. v_r successively bound to resulting rows.
5. e_a :: τ[]. No SLICE: v_a :: τ bound to array elements. SLICE n: v_a :: τ[] bound to sub-arrays in nth dimension.

Leaving/Short-Cutting Loops

All five LOOP forms support optional << ‹*label*› >> prefixes:

```
<< ‹label› >> … LOOP s⅁ END LOOP
```

We may alter the control flow inside a loop via:

```
1       EXIT [‹label›] [ WHEN p ]
2   CONTINUE [‹label›] [ WHEN p ]
```

- No ‹*label*›: refer to innermost enclosing loop.
- WHEN *p*: leave/shortcut loop only if *p* ≡ true.
- EXIT ‹*label*› may also be used to leave a statement block.

Leaving/Shortcutting Loops

```
<< outer >>
LOOP
  s0
  ⋮
  << inner >>                     ····shortcut
  LOOP
    ⋮
    CONTINUE outer;
    ⋮
    EXIT inner;
    ⋮                          ····leave
  END LOOP;
  s1
  ⋮
END LOOP;
```

- Shortcutting a WHILE *p* loop leads to re-evaluation of *p*.

10 ┆ Trapping Exceptions in Blocks

```
BEGIN
  ⋮     --  ⎫  errors or RAISE ex statements transfer control
  sₓ    --  ⎬  to the EXCEPTION clause — if sₓ changed the
  ⋮     --  ⎭  database, also performs a rollback
EXCEPTION
  [ WHEN exᵢ₁ [, exᵢⱼ]* THEN sᵢ ]⁺
END;
s₁      -- next statement if no exception occurred
```

- On error or RAISE, search for first matching exception category/name ex_{ij}, execute s_i, then s_1.
- If no match is found (or s_i fails), propagate exception to enclosing block. Abort function if in outermost block.

Raising Exceptions

```
                    one expression per '%' in message

1   RAISE [ ‹level› ] '… % … % …' [, e]*
2   RAISE [ ‹level› ] ex
3   ASSERT p [, e]
```

- *level* ∈ {DEBUG,LOG,INFO,NOTICE,WARNING}. Only the default *level* ≡ EXCEPTION raises an exception of name RAISE_EXCEPTION (or *ex*[6], if provided).

- ASSERT *p* (*p* :: bool) raises exception ASSERT_FAILURE—with optional message *e* :: text—if *p* ≡ false.

[6] See https://www.postgresql.org/docs/current/errcodes-appendix.html for a catalog of exception categories/names.

11 The Core of a Spreadsheet

	A	B	C	D
1	1	3.50	A1×B1	€→£ 0.88
2	2	6.10	A2×B2	
3	2	0.98	A3×B3	
4	#items SUM(A1:A3)		total (€) SUM(C1:C3)	total (£) D1×C4

Before evaluation

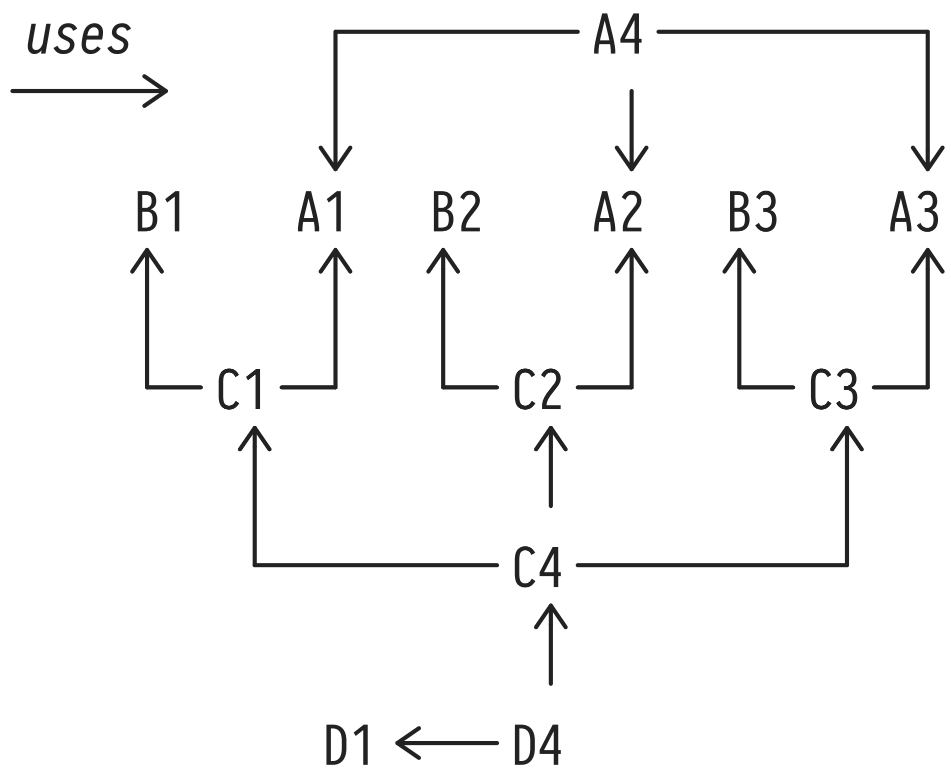
	A	B	C	D
1	1	3.50	3.50	€→£ 0.88
2	2	6.10	12.20	
3	2	0.98	1.96	
4	#items 5		total (€) 17.66	total (£) 15.54

After evaluation

- A1×B1: formulæ to be evaluated, <u>total (€)</u>: static text.

A DAG of Cell Dependencies

- Spreadsheet formulæ induce a directed **dependency graph:**



- Formulæ in A1–A3, B1–B3, D1 may be evaluated first (and in parallel).
- Formula in cell D4 needs to be evaluated last.
- **Topologically sort** the graph's cells to derive an **evaluation order.**

Topologically Sort a DAG dependencies(cell, uses)

```
WITH RECURSIVE
earliest(pos, cell) AS (
  SELECT DISTINCT 0 AS pos, d.uses AS cell
  FROM   dependencies AS d
  WHERE  d.uses NOT IN (SELECT d1.cell                  -- } cells d with no
                        FROM   dependencies AS d1) -- } dependencies

    UNION

  SELECT e.pos + 1 AS pos, d.cell              -- } if cell d uses cell e, d
  FROM   earliest AS e, dependencies AS d -- } can be evaluated directly
  WHERE  d.uses = e.cell                       -- } after e at the earliest
),
topo_sort(pos, cell) AS (
  SELECT MAX(e.pos) AS pos, e.cell        -- } for each cell e, pick the
  FROM   earliest AS e                    -- } evaluation time at which all
  GROUP BY e.cell                         -- } dependencies are available
)
```

Dependencies, Topologically Sorted

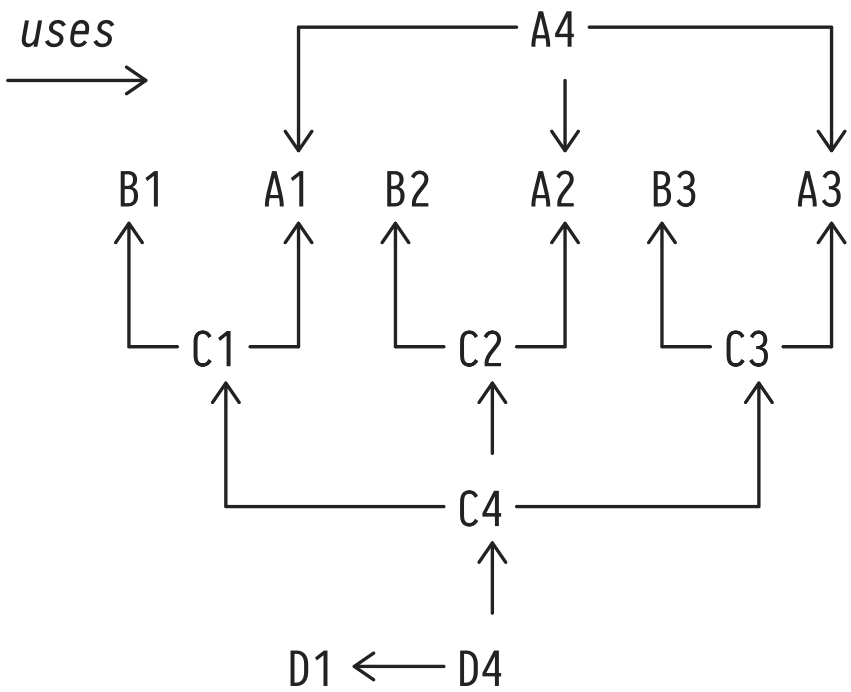


Table **topo_sort**

pos	cell
0	(A,1)
0	(A,2)
0	(A,3)
0	(B,1)
0	(B,2)
0	(B,3)
0	(D,1)
1	(A,4)
1	(C,1)
1	(C,2)
1	(C,3)
2	(C,4)
3	(D,4)

- Column **pos** describes parallel evaluation order.
- Use **DENSE_RANK**() to obtain a sequential order.

Formula Representation

- We need a representation of formulæ that supports
  1. the **extraction of references** to other cells and
  2. the **evaluation** of (arithmetic) expressions.

- One option: use **nested JSON objects** to reflect the hierarchical structure of formulæ:

❶ literal ¦ ❷ cell ref ¦ ❸ *n*-ary op ¦ ❹ agg over cell range

```
❶ {"entry":"num",  "num":4.2}
❷ {"entry":"cell", "cell":"(A,3)"}
❸ {"entry":"op",   "op":"+", args:[‹formula›,‹formula›]}
❹ {"entry":"agg",  "agg":"sum", "from":"(A,2)", "to":"(D,5)"}
```

formula kind — formula details (“payload”)

Extracing Cell References in a Formula (PL/SQL)

```
CREATE FUNCTION refs(e jsonb) RETURNS SETOF cell AS
$$
BEGIN
  CASE e->>'entry'
    WHEN 'op' THEN
        -- recursively collect references found in operator arguments
        RETURN QUERY SELECT c.*
                     FROM   jsonb_array_elements(e->'args') AS arg,
                            LATERAL refs(arg) AS c; -- ◀ recursive call
    WHEN 'agg'  THEN
        -- all cells in rectangular area are referenced (SQL UDF cells())
        RETURN QUERY SELECT c.*
                     FROM   cells(e->>'from', e->>'to') AS c;
    WHEN 'cell' THEN RETURN NEXT e->>'cell';   -- reference to single cell
    WHEN 'num'  THEN NULL;                     -- NULL: do nothing (≡ NOP)
    ELSE RAISE EXCEPTION 'refs: unknown cell entry %', e->>'entry';
  END CASE;
  RETURN;
END;
$$
```

Evaluate a Formula (PL/SQL)

```
CREATE FUNCTION eval(e jsonb) RETURNS float AS
$$                          --  PL/SQL UDF value(c) may assume that cell c contains
DECLARE v float;            --  a float literal: if we refer to c, the topological
BEGIN                       --  sort ensures that c has already been evaluated
  CASE e->>'entry'          --
    WHEN 'op' THEN          --
      CASE e->>'op'
        WHEN '+' THEN v := eval(e->'args'->0) + eval(e->'args'->1);
        ⋮
      END CASE;
    WHEN 'agg' THEN v:= (SELECT CASE e->>'agg'
                                  WHEN 'sum' THEN SUM(value(c))
                                  ⋮
                                END
                         FROM   cells(e->>'from', e->>'to') AS c);
    WHEN 'cell' THEN v := value(e->>'cell');
    WHEN 'num'  THEN v := e->>'num';
  END CASE;
  RETURN v;
END;
$$
```

Spreadsheet Evaluation (Query Plan)

1. Store the cells in table `sheet(cell, formula :: jsonb)`.
2. Extract dependencies of each cell's formula (`refs()`), use to build topologically sorted array *cs* of cells.
3. PL/SQL UDF `eval_sheet()`:
   For each cell *c* in *cs*:
   ❶ Read formula *e* for *c* off table `sheet`.
   ❷ *v* := `eval(`*e*`)` to find float value *v* of formula *e*.
   ❸ **Update** cell *c* in `sheet` to `{"entry":"num", "num":`*v*`}`.
4. All cells in `sheet` will contain `{"entry":"num", …}`.

Spreadsheet Evaluation (PL/SQL)

```
  CREATE FUNCTION eval_sheet(cs cell[]) RETURNS boolean AS
  $$
  DECLARE c cell; v float; e jsonb;
  BEGIN
    FOREACH c IN ARRAY cs LOOP
      SELECT s.formula
1     INTO   e
      FROM   sheet AS s
      WHERE  s.cell = c;

2     v := eval(e);

      UPDATE sheet AS s
3     SET    formula = jsonb_build_object('entry', 'num', 'num', v)
      WHERE  s.cell = c;
    END LOOP;
  RETURN true;
  END;
  $$
```

PL/SQL—The Best Thing Since Sliced 🍞?

- PL/SQL…

  1. … follows the established **imperative programming paradigm** in which so many developers are well-versed,
  2. … is **tightly coupled with the RDBMS**'s data model, type system, and built-in operators/functions:

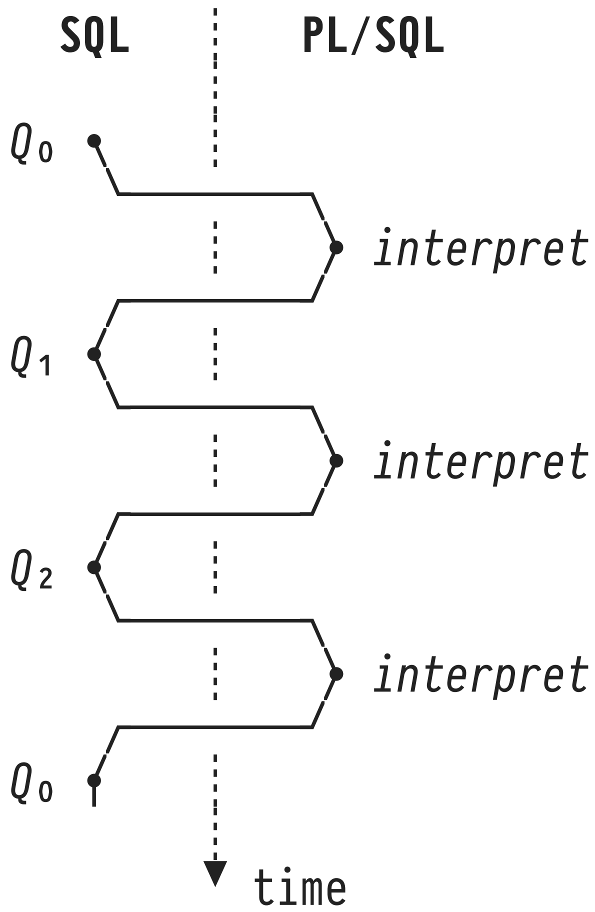
  Why would we ever consider to express complex computation in terms of pure SQL (e.g., recursive CTEs) again?

- ⚠️ Many PL/SQL implementations incur a serious performance penalty due to **PL/SQL↔SQL context switches.**

From SQL to PL/SQL And Back Again

```
CREATE FUNCTION f(…) RETURNS τ AS
$$
   ====
   v1 = (
          );                      ] embedded
                                  ] SQL Q1
   ===========
   ========================
     ============
     ============
   ===
     =====
     v2 = (
            );                    ] embedded
                                  ] SQL Q2
     =====
   ==========
$$ LANGUAGE PLPGSQL;

SELECT f(…);                      ] top-level
                                  ] SQL Q0
```

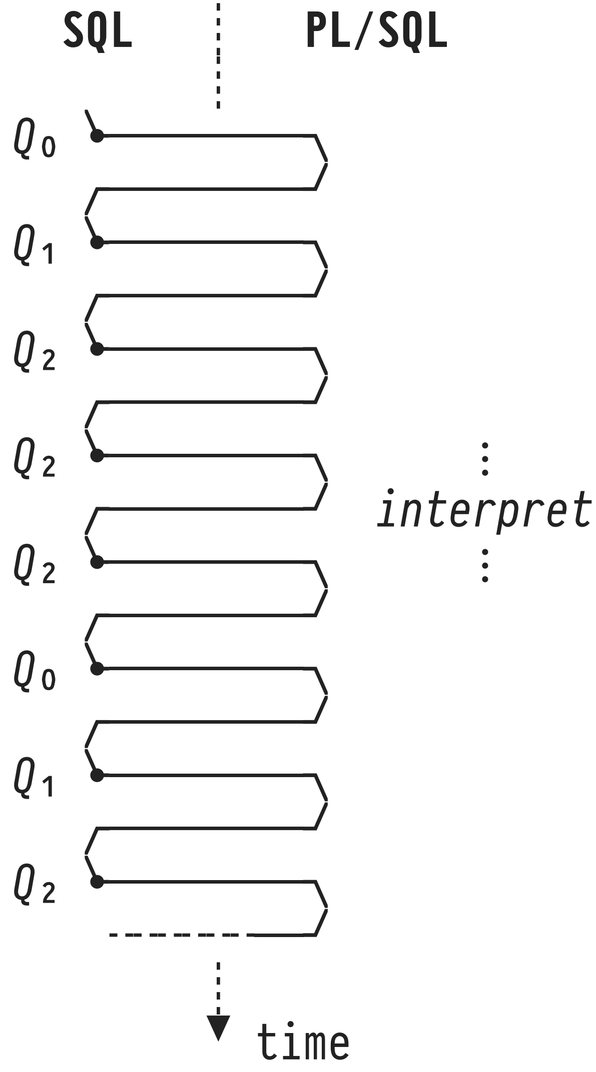


SQL↔PL/SQL (Iteration Inside and Outside the UDF)

```
CREATE FUNCTION f(⋯) RETURNS τ AS
$$
   v1 = (                );          ] embedded
                                     ] SQL Q1
   WHILE     LOOP
   |
   |
   |
   |
   |  v2 = (                );       ] embedded
   |                                 ] SQL Q2
   LOOP END

$$ LANGUAGE PLPGSQL;

SELECT f(⋯,t,⋯);                     ] top-level
FROM   T AS t                        ] SQL Q0
```



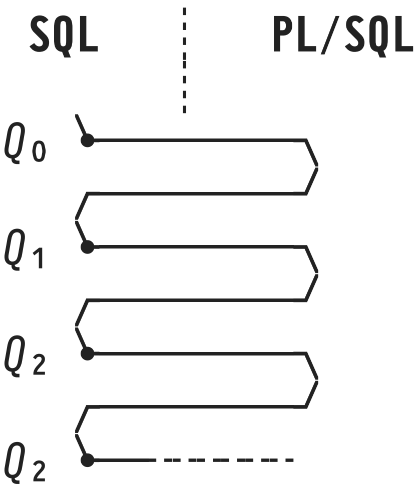
SQL↔PL/SQL Context Switches Are Costly

plan + optimize + **instantiate** + run + **teardown** ··· Q_0

plan + optimize + **instantiate** + run + **teardown** ··· Q_1

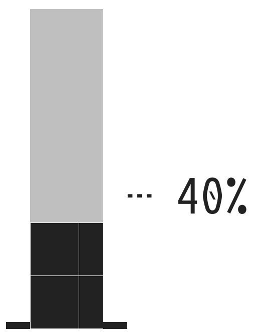
plan + optimize + **instantiate** + run + **teardown** ··· Q_2

instantiate + run + **teardown** ··· Q_2



PostgreSQL Runtime Profile ⏰

PL/SQL interpreter
invocation overhead



That's All, Folks

Keep on querying and until next time.