Advanced SQL

06 — Procedural SQL

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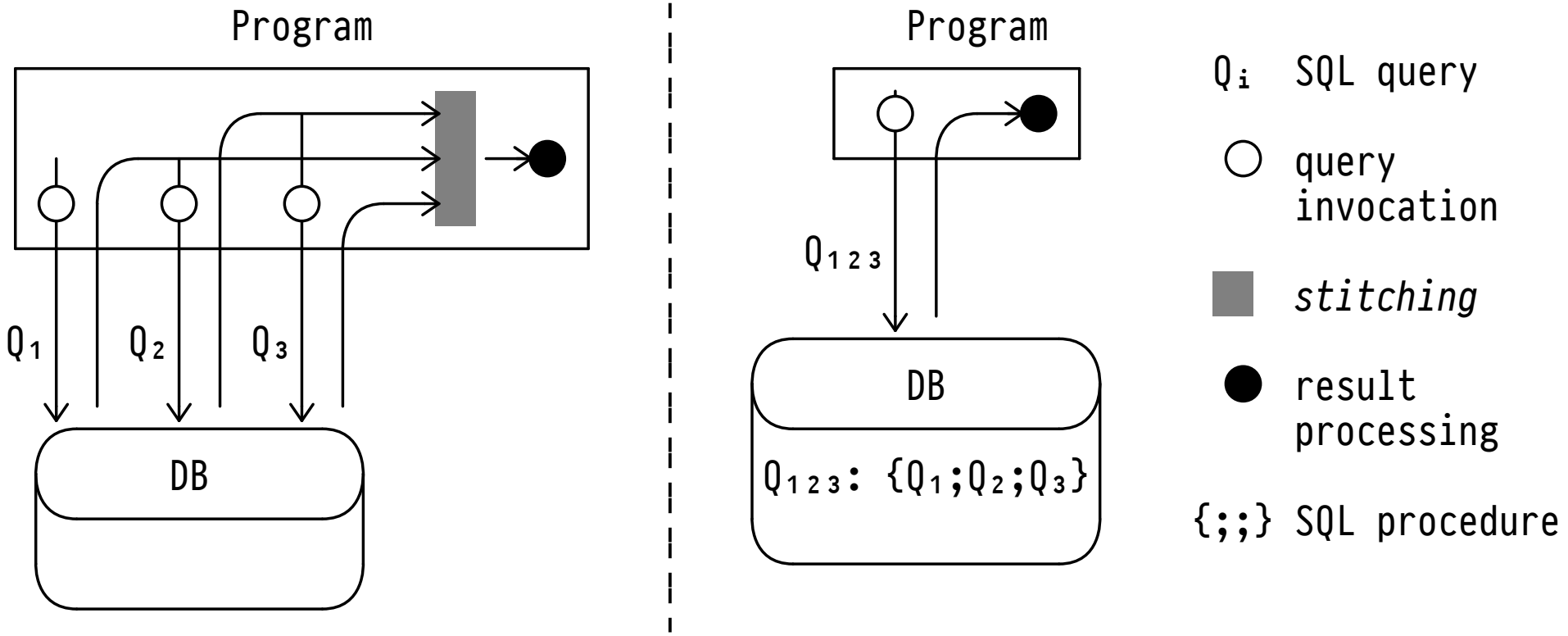
1 Scripting Language + SQL = Procedural SQL

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(x1 τ1, …, xn τn) 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 $\tau \equiv \texttt{SETOF}\ \bar{\tau}$.

[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).

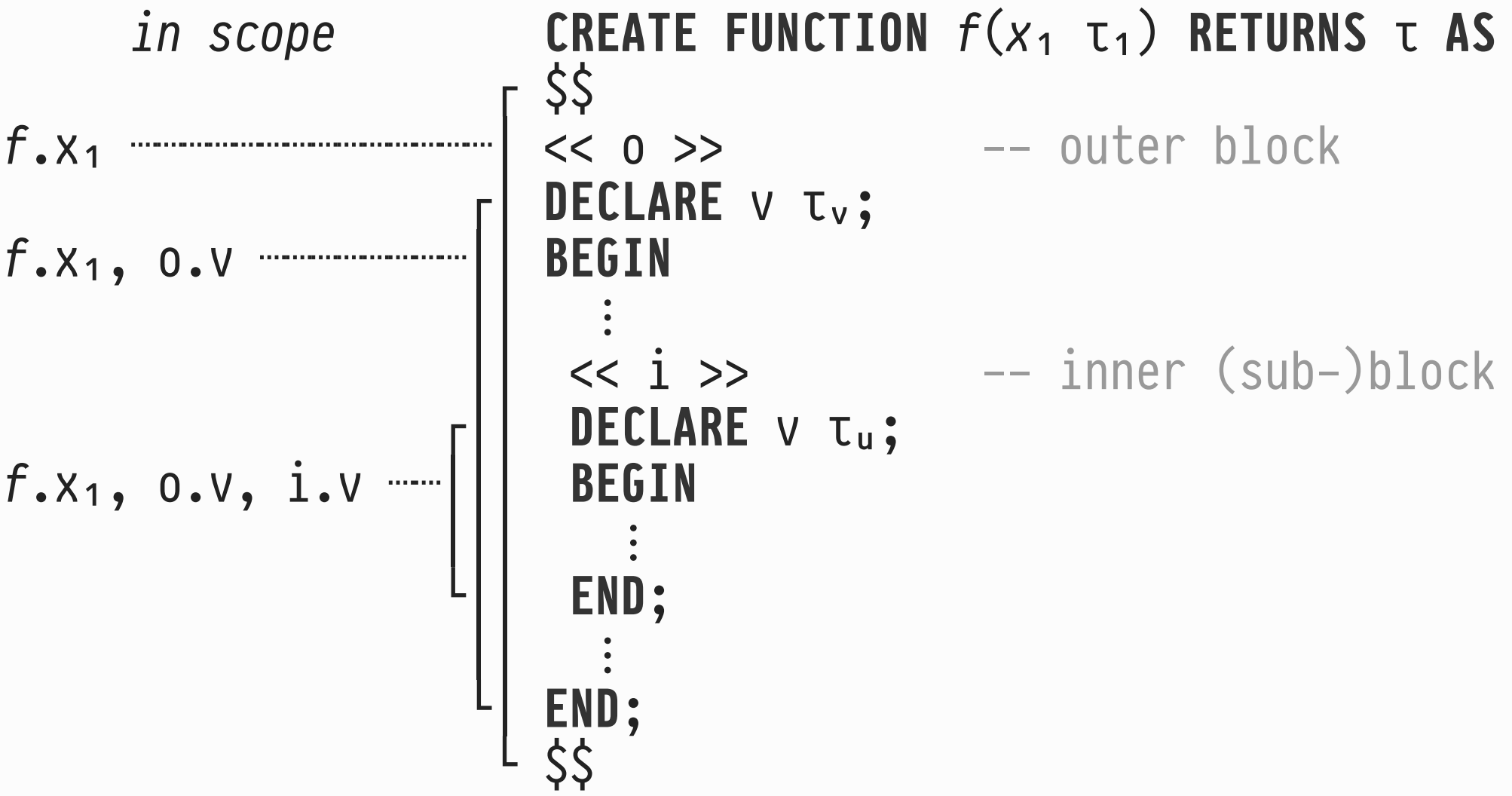
2 Block Structure ✎

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

```
[ DECLARE ‹declarations› ]
BEGIN
  ‹statements›              -- ◀ 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]



[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 *c*. ✎

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 access_i(t T) RETURNS T.c_i%TYPE AS
$$
--          ▮+▮ table + column name
DECLARE x T.c_i%TYPE; -- x has type τ_i
BEGIN
  x := t.c_i;             -- field access uses dot notation
  RETURN x;
END;
$$
LANGUAGE PLPGSQL;
```

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 implications: context switches PL/pgSQL↔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… 🙈

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 *q* may be performed solely for its side effects (e.g., invocation of a side-effecting UDF) as well:

```
PERFORM q  -- ⚠ 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 rows to result.

- Use plain `RETURN;` to return the entire result table and resume execution in the caller.

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

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

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

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

```
❶                                                  LOOP s↺ END LOOP
❷                                              WHILE p LOOP s↺ END LOOP
❸   FOR vᵢ IN [ REVERSE ] e₀..e₁ [ BY e₂ ] LOOP s↺ END LOOP
❹                                          FOR vᵣ IN q LOOP s↺ END LOOP
❺      FOREACH vₐ IN [ SLICE n ] ARRAY eₐ LOOP s↺ END LOOP
```

❶ Endless loop (see EXIT below).

❷ p :: bool.

❸ $e_{0,1,2}$ :: 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: $\pm \equiv -$).

❹ q SQL query. v_r successively bound to resulting rows.

❺ 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:

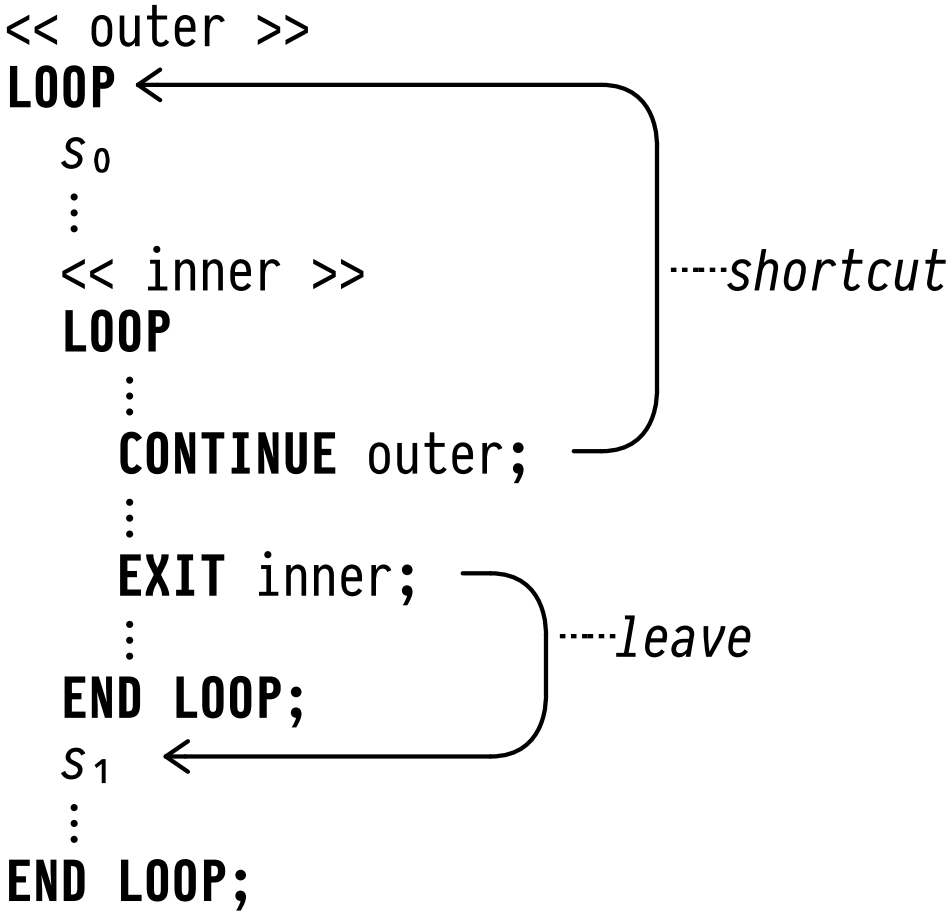
```
<< ‹label› >> … LOOP sG END LOOP
```

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 ✎



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

```
BEGIN
  ⋮    --  errors or RAISE ex statements transfer control
  sx   --  to the EXCEPTION clause – if sx changed the
  ⋮    --  database, also performs a rollback
EXCEPTION
  [ WHEN ex_i1 [, ex_ij]* THEN s_i ]+
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*[5], if provided).
- ASSERT *p* (*p* :: bool) raises exception ASSERT_FAILURE — with optional message *e* :: text — if *p* ≡ false.

[5] See https://www.postgresql.org/docs/9.6/static/errcodes-appendix.html for a catalog of exception categories/names.

\	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

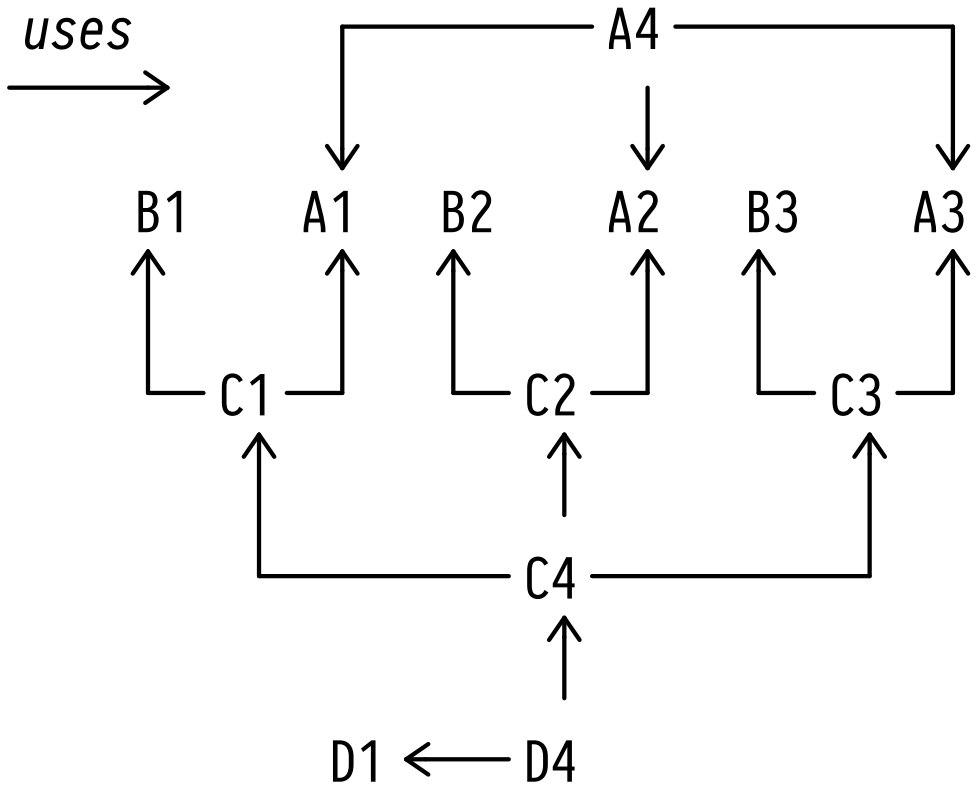
\	A	B	C	D
1	1	3.50	3.50	€→£ 0.88
2	2	6.10	12.20	
3	2	0.98	1.96	
4	#items 5		total (€) 17.66	total (£) 15.54

After evaluation

- A1×B1: formulæ to be evaluated, total (€): 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

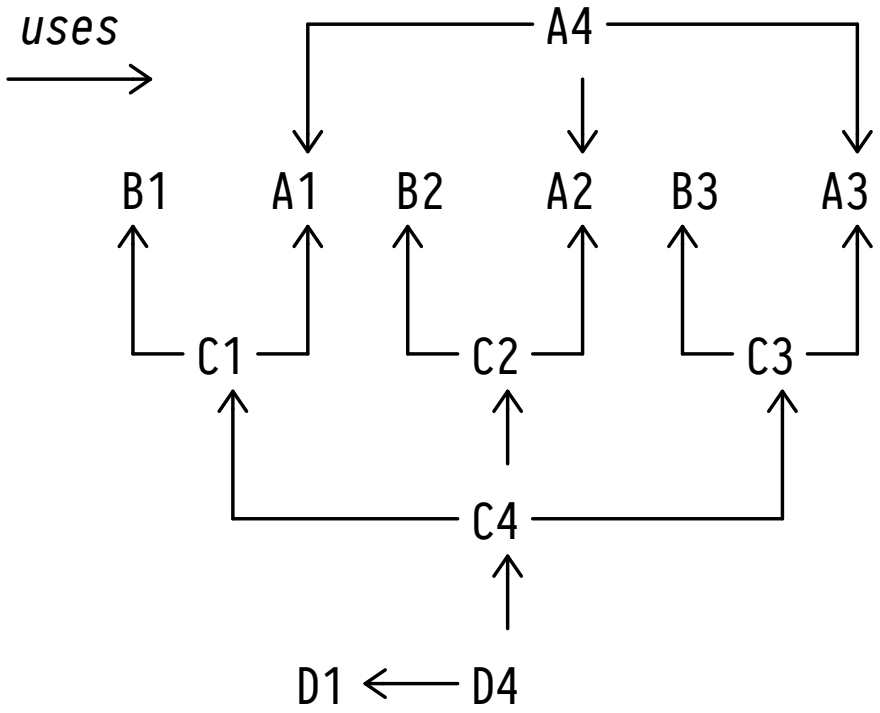


Table **topo_sort**

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

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;
$$
```

That's All, Folks

Keep on querying and until next time.