Advanced SQL

- -

04 — Arrays and User-Defined Functions

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1 ┊ Arrays: Aliens(?) Inside Table Cells

SQL tables adhere to the **First Normal Form** (1NF): values v inside table cells are *atomic* w.r.t. the tabular data model:

...	A	...
...	v	...

Let us now discuss the **array** data type:

- v may hold an ordered array of elements $\{x_1,...,x_n\}$.[1]
- SQL treats v as an atomic unit, but ...
- ... array functions and operators also enable SQL to query the x_i individually (still, that's no ⚡ with 1NF).

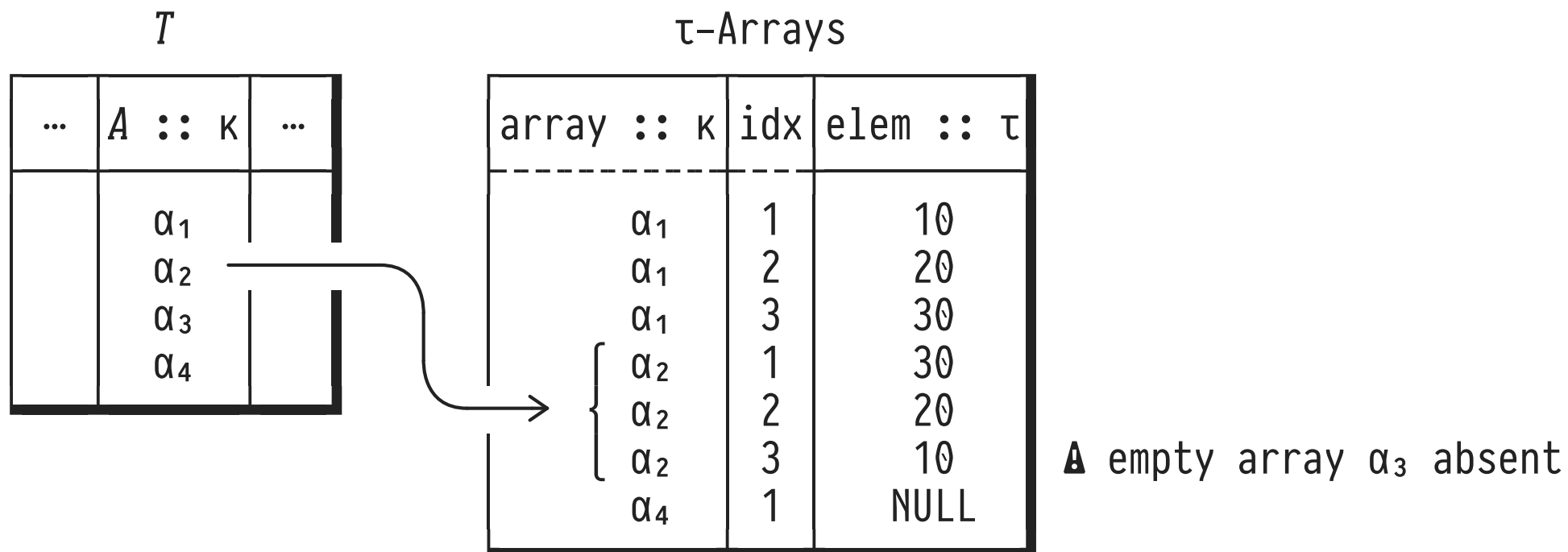[1] To the PostgreSQL developer who decided to use $\{...\}$ to denote *arrays*: **No dessert for you today!**

2 ⦙ Array Types

- For type τ, τ[] (or τ array) is the type of **homogenous arrays of elements of τ.**

  - τ may be built-in or user-defined (enums, row types).
  - Array size is unspecified—the array is dynamic. (PostgreSQL accepts τ[n] but the n is ignored.)

⋯	A :: int[]	⋯
⋯	{10,20,30}	⋯
⋯	{30,20,10}	⋯
⋯	{}	⋯
⋯	{NULL}	⋯

T

"Simulating" Arrays (Tabular Array Semantics)

T | τ-Arrays

array :: κ	idx	elem :: τ
α_1	1	10
α_1	2	20
α_1	3	30
α_2	1	30
α_2	2	20
α_2	3	10
α_4	1	NULL

T table: $A :: \kappa$ with rows α_1, α_2, α_3, α_4

△ empty array α_3 absent

- κ denotes a suitable key data type.
- Arrays indexes are of type int and 1-based.

3 ┊ Array Literals

One-dimensional array literals of type $\tau[]$:

array[] :: $\tau[]$ empty array of elements of type τ

array[$<x_1>,…,<x_n>$]   } all x_i of type τ
'{$<x_1>,…,<x_n>$}' :: $\tau[]$ }

Multi-dimensional rectangular array literals of type $\tau[][]$:

⚠ all sub-arrays need to agree in size

array[array[$<x_{11}>,…,<x_{1n}>$],…,array[$<x_{k1}>,…,<x_{kn}>$]]
'$<x_{11}>,…,<x_{1n}>$},…,{$<x_{k1}>,…,<x_{kn}>$' :: $\tau[][]$

1 ■■■■
⋮ ■■■■
k ■■■■
1……n

Example: Tree Encoding (parents[i] ≡ parent of node i)

t_1

t_2

t_3
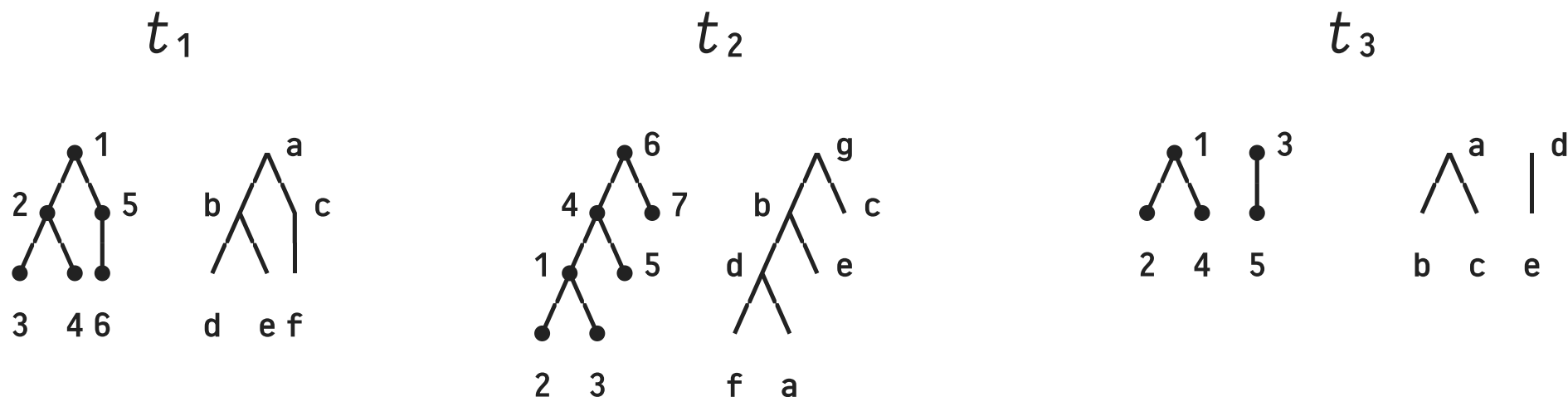
Tree shape and node labels held in separate in-sync arrays:

tree	parents	labels
t_1	{NULL,1,2,2,1,5}	{'a','b','d','e','c','f'}
t_2	{4,1,1,6,4,NULL,6}	{'d','f','a','b','e','g','c'}
t_3	{NULL,1,NULL,1,3}	{'a','b','d','c','e'}
	1 2 3 4 5	1 2 3 4 5 ←-- @idx

Trees

Constructing Arrays

- **Append**/**prepend** element ✳ to array or
- **con**cat**enate** arrays:

$$
\begin{array}{ll}
\text{array\_append } (\text{array}[x_1,\ldots,x_n],✳) & \equiv \quad \text{array}[x_1,\ldots,x_n,✳] \\
\text{array\_prepend}(\text{array}[x_1,\ldots,x_n],✳) & \equiv \quad \text{array}[x,x_1,\ldots,x_n]
\end{array}
$$

$$
\begin{array}{ll}
\text{array\_cat}(\text{array}[x_1,\ldots,x_n], & \\
\qquad\quad \text{array}[y_1,\ldots,y_m]) & \equiv \quad \text{array}[x_1,\ldots,x_n,y_1,\ldots,y_m]
\end{array}
$$

- Overloaded operator || embraces all of the above:

$$
\begin{array}{l}
xs \;||\; ✳ \equiv \text{array\_append}(xs,\ ✳) \\
\;✳ \;||\; xs \equiv \text{array\_prepend}(xs,\ ✳) \\
xs \;||\; ys \equiv \text{array\_cat}(xs,ys)
\end{array}
$$

Accessing Arrays: Indexing / Slicing

- Array **indexes** i are 1-based (let $xs \equiv array[x_1,…,x_n]$):

$$
\begin{aligned}
xs[i] &\equiv x_i & i \notin \{1,…,n\}: \text{NULL} \\
(\text{NULL})[i] &\equiv \text{NULL} \\
xs[\text{NULL}] &\equiv \text{NULL} \\
xs[i{:}j] &\equiv array[x_i,…,x_j] & i > j: array[] \\
xs[i{:}\ ] &\equiv array[x_i,…,x_n] \\
xs[\ {:}j] &\equiv array[x_1,…,x_j]
\end{aligned}
$$

- Access **last element** x_n:

```
xs[array_length(xs,1)]     # of elements in dimension 1: n
xs[cardinality(xs)]
        ▲
 Σ (# of elements) in all dimensions
```

Searching for Elements in Arrays

Indexing accesses array by position. **Searching** accesses arrays by **contents,** instead.

- Let $xs \equiv \text{array}[x_1,\ldots,x_{i-1},*,x_{i+1},\ldots,x_{j-1},*,x_{j+1},\ldots,x_n]$ and comparison operator $\theta \in \{=,<,>,<>,<=,>=\}$:

$$x \ \theta \ \text{ANY}(xs) \qquad \equiv \exists \ i \in \{1,\cdots,n\}: x \ \theta \ xs[i]$$
$$x \ \theta \ \text{ALL}(xs) \qquad \equiv \forall \ i \in \{1,\cdots,n\}: x \ \theta \ xs[i]$$

$$\text{array\_position}(xs,*) \ \equiv i \qquad\qquad \text{if } * \text{ not found: NULL}$$
$$\text{array\_positions}(xs,*) \equiv \text{array}[i,j] \quad \text{if } * \text{ not found: array}[]$$

$$\text{array\_replace}(xs,*,\#) \equiv \text{array}[x_1,\ldots,\underset{i}{\#},\ldots,\underset{j}{\#},\ldots,x_n]$$

4 ⋮ A Bridge Between Arrays and Tables: **unnest** & **array_agg**

```
SELECT t.elem
FROM   unnest(array[x₁,…,xₙ]) AS t(elem)
```

$$\underbrace{\quad\quad\quad\quad}_{\equiv\; xs}$$

$\equiv$

Table t

elem
x_1
$\vdots$
x_n

```
SELECT array_agg(t.elem) AS xs
FROM   (VALUES (x₁),
                  ⋮
               (xₙ)) AS t(elem)
```

$\equiv$

xs
$\{x_1,…,x_n\}$

- unnest(•): a *set-returning function*. More on that soon.
- ⚠️ Preservation of order of the x_i is *not* guaranteed…

Representing Order (Indices) As First-Class Values

```
SELECT  t.*
FROM    unnest(array[x₁,…,xₙ])
        WITH ORDINALITY AS t(elem,idx)
                              ▲
```

$\equiv$

elem	idx
x_1	1
⋮	⋮
x_n	n

recall ordered aggregates

```
SELECT  array_agg(t.elem ORDER BY t.idx) AS xs
FROM    (VALUES (x₁,1),
                   ⋮
                (xₙ,n)) AS t(elem,idx)
```
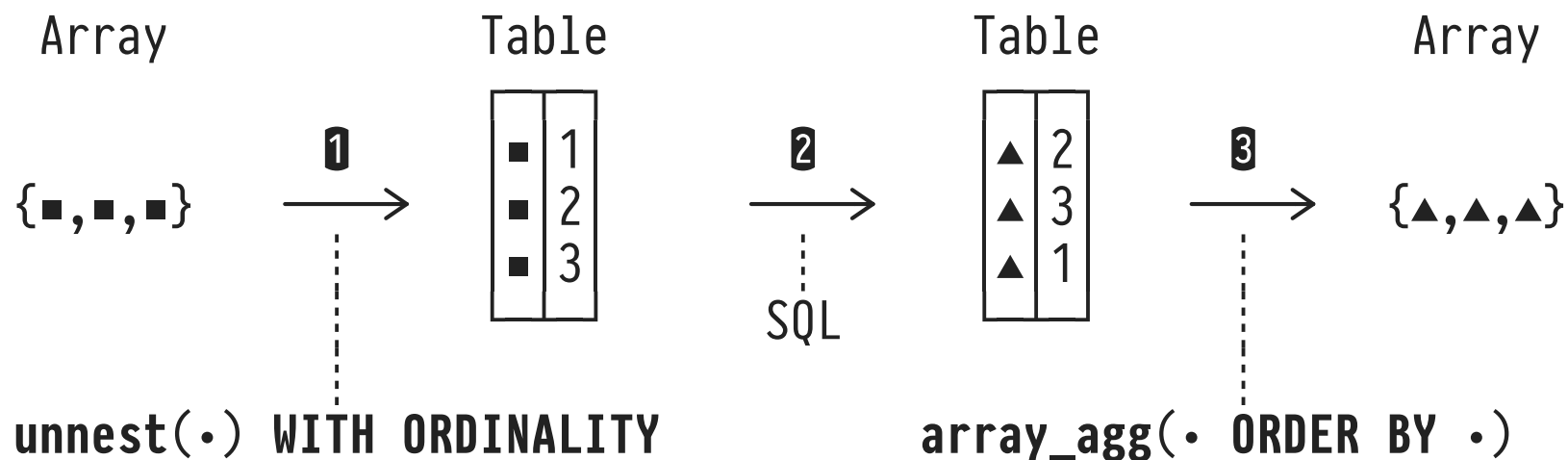
$\equiv$

xs
$\{x_1,…,x_n\}$

- $\langle f \rangle(\cdots)$ WITH ORDINALITY adds a trailing column (▲) of ascending indices $1,2,\ldots$ to the output of function f.

A Relational Array Programming Pattern

Availability of unnest($\bullet$) and ordered array_agg($\bullet$) suggests a pattern for **relational array programming:**

- At ❷ use the full force of SQL, read/transform/generate elements and their positions at will.
- ❶+❸ constitute **overhead:** an RDBMS is *not* an array PL.

5 ┊ Table-Generating Functions

What is the **type** of unnest(•)?

- unnest(•) establishes a bridge between arrays and SQL's tabular data model:[2]

$$\text{unnest} :: \tau[] \to \text{SETOF } \tau$$

- In SQL, functions of type $\tau_1 \to \text{SETOF } \tau_2$ are known as **set-returning** or **table(-generating) functions.** May be invoked wherever a query expects a table (FROM clause).

- Several built-in, but may also be **defined by the user.**

[2] Unfortunate naming again: SETOF should probably read BAGOF or TABLE OF.
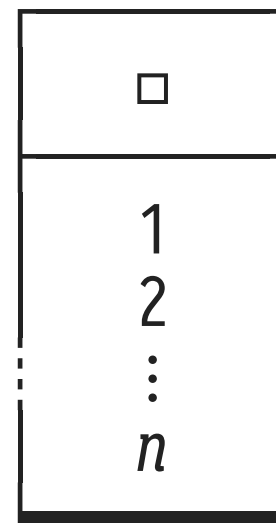
Series and Subscript Generators

Built-in table-generating functions that generate **tables of consecutive numbers:**

generate_series(‹*f*›,‹*t*›,‹*s*›)

□
f
f+1×*s*
f+2×*s*
⋮
f+*n*×*s*

≤ *t* ➡
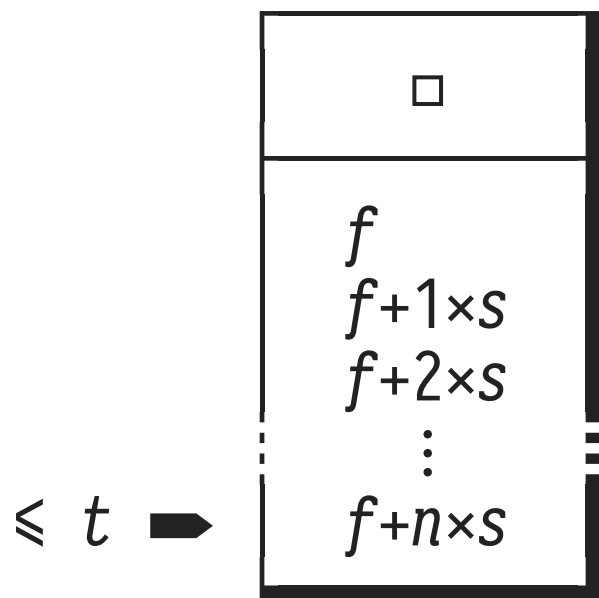
‹*s*› ≡ 1, if absent
‹*f*›,‹*t*›: numbers/timestamps

generate_subscripts(‹*xs*›,‹*d*›)

□
1
2
⋮
n

n ≡ array_length(‹*xs*›,‹*d*›)
can also enumerate *n*,…,1

Text Generators (Regular Expression Matching)

Use *regular expression*[3] *re* to extract **matched substrings** from *t* or **split** text *t* at defined positions:

1. regexp_matches(‹*t*›,‹*re*›,'g'), yields SETOF text[]:
   Generates one array *xs* per match of *re* in *t*. Element ‹*xs*›[*i*] holds the **match** of the ith *capture group* (in (…)).

2. regexp_split_to_table(‹*t*›,‹*re*›), yields SETOF text:
   Uses the matches of *re* in *t* as *separators* to **split** *t*. Yields table of *n*+1 rows if *re* matches *n* times.

[3] See regexr.com for tutorials and an interactive playground, for example.

Breaking Bad: Parse a Chemical Formula (e.g., $C_6H_5O_7^{3-}$)

```
SELECT  t.match[1] AS element,      --  ⎤ extract match details
        t.match[2] AS "# atoms",    --  ⎬ from the (…)
        t.match[3] AS charge        --  ⎦ (capture groups)
FROM    regexp_matches(
          'C₆H₅O₇³⁻',
          '([A-Za-z]+)([₀-₉]*)([⁰-⁹]+[⁺-])?',
          'g')
        AS t(match);
```
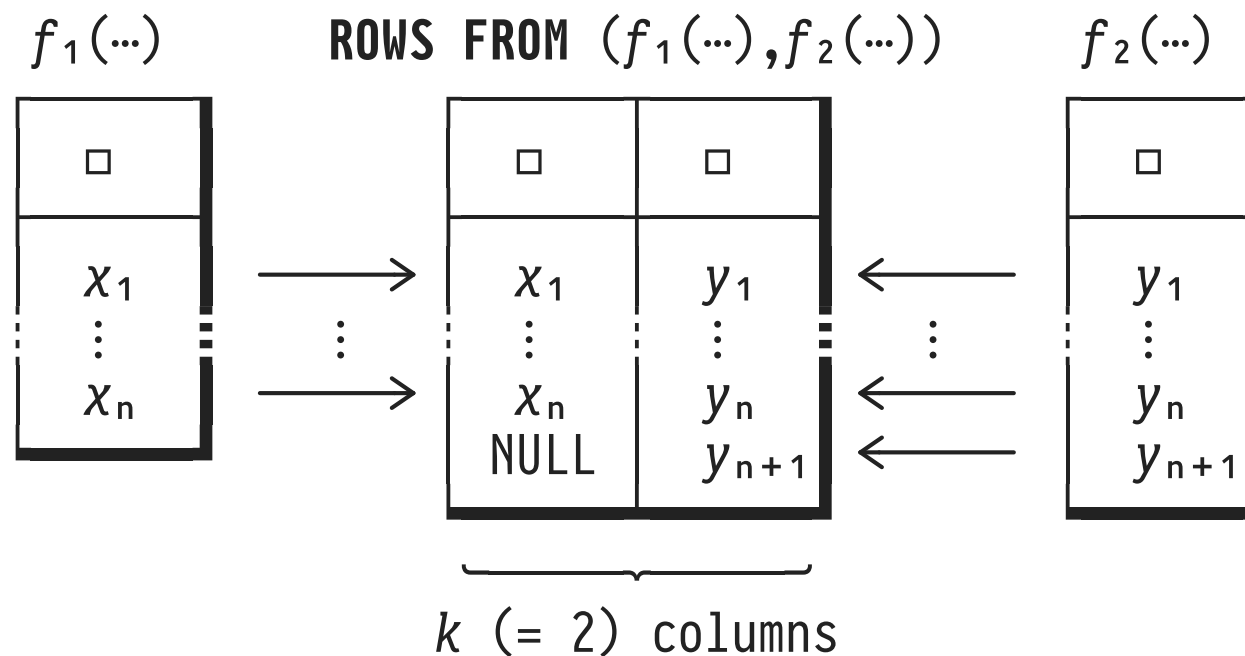
element	# atoms	charge
C	6	NULL
H	5	NULL
O	7	3−

} NULL ≡ no match

Zipping Arrays and Table‑Generating Functions

Zip: pair elements based on position ("ORDINALITY join"):

- Zipping table functions f_i: **ROWS FROM**$(f_1(\cdots),\ldots,f_k(\cdots))$
- Zipping arrays xs_i: **unnest**$(xs_1,xs_2,\ldots,xs_k)$

k (= 2) columns

6 ┊ User-Defined SQL Functions (UDFs)

The body of a **user-defined SQL function (UDFs)** evaluates $n \geqslant 1$ arbitrary SQL statements in sequence:

```
CREATE FUNCTION <f>(<x₁> τ₁,…,<xₖ> τₖ) RETURNS τ AS
$$
  <q₁>;      --  ⎤
  <q₂>;      --  ⎬  evaluate the qᵢ in order,
    ⋮        --  ┊  qₙ defines the result
  <qₙ>       --  ⎦
$$
LANGUAGE SQL [IMMUTABLE];
                    ▲

  all qᵢ are read-only ⇒ f is free of side effects
```

- UDF f is stored persistently. Remove via DROP FUNCTION.

UDF Types

- UDF f is k-ary with type $\tau_1 \times \cdots \times \tau_k \rightarrow \tau$.

  - **Argument types** τ_i must be **atomic** or **row types.**
  - **Overloading** allowed as long as $(f, \tau_1, \ldots, \tau_k)$ is unique.
  - Limited form of **polymorphism**: any τ_i and τ may be anyelement/anyarray/anyenum/anyrange.
    - ⚠️ If any··· occurs more than once in the function signature, *all* occurrences denote the *same* type:

$$f_1 :: \overbrace{\text{anyelement} \times \text{anyelement}}^{=} \rightarrow \text{boolean}$$
$$f_2 :: \underbrace{\text{anyarray} \times \text{integer} \rightarrow \text{anyelement}}_{\texttt{elem} =}$$

UDFs Can Return Tables

A UDF $f :: \tau_1 \times \cdots \times \tau_k \rightarrow \tau$ may be of **two flavors:**

	atomic τ	$\tau \equiv$ SETOF τ'
If q_n[4] returns no rows,	returns NULL	returns empty table
If q_n returns rows,	returns the first row	returns all rows
May be invoked	wherever $v::\tau$ is used	in the FROM clause

Regular vs. Table-generating UDFs

- A UDF may invoke INSERT/DELETE/UPDATE statements in q_i and thus incur side-effects. (Hmm, UD*F*...⚡)
  - No IMMUTABLE option—use VOLATILE instead.
  - Use $\tau \equiv$ void if f is all about side-effects or consider adding … RETURNING $\langle e_1 \rangle,\ldots,\langle e_m \rangle$ if $i = n$.

---

[4] Recall: f's body evaluates queries $q_1,\ldots,q_n$ (in this order).

Example UDF: Map Unicode Subscripts

Map subscript symbol $'_0'$,...,$'_9'$ to its value in $\{0,...,9\}$:

```sql
CREATE FUNCTION subscript(s text) RETURNS int AS
$$
  SELECT subs.value::int - 1
  FROM    unnest(array['₀','₁','₂',…,'₉'])
          WITH ORDINALITY AS subs(sym,value)
  WHERE   subs.sym = s
$$
LANGUAGE SQL IMMUTABLE;
```

- This is a UDF with atomic return type: yields NULL if s does not denote a valid subscript.

Example UDF: Issue Unique ID, Write Protocol

Generate ID of the form '<prefix>###' and log time of issue:

```sql
CREATE FUNCTION new_ID(prefix text) RETURNS text AS
$$
  INSERT INTO issue(id,"when") VALUES
    (DEFAULT, 'now'::timestamp)
  RETURNING prefix || id::text       -- id: just generated
$$
LANGUAGE SQL VOLATILE;       -- function is side-effecting
```

id	when
⋮	⋮
42	2020-05-12 17:26:14.188803
⋮	⋮

Table issue

Example Table-Generating UDF: Flatten a 2D-Array

Unnest 2D array *xss* in *column-major order*:[5]

```
CREATE OR REPLACE FUNCTION unnest2(xss anyarray)
  RETURNS SETOF anyelement AS
$$
  SELECT xss[i][j]
  FROM   generate_subscripts(xss,1) _(i),
         generate_subscripts(xss,2) __(j)
  ORDER BY j, i  --  return elements in column-major order
$$
LANGUAGE SQL IMMUTABLE;
```

- ⚠️ Intended type is unnest2 :: τ[][] → SETOF τ.

[5] Built-in function unnest(•) can flatten *n*-dimensional arrays in row-major order.

Table-Generating UDFs: Returning Typed Rows

Assume a table-generating UDF $f :: \ldots \to \tau$.

$$\text{If } \tau \equiv$$

| SETOF τ' τ' atomic | SETOF τ' $\tau' \equiv (c_1 :: \tau_1, \ldots, c_m :: \tau_m)$ | TABLE $(c_1\ \tau_1, \ldots, c_m\ \tau_m)$ |

$v_i :: \tau'$ equivalent, but do not need named row type τ'

7 ⋮ ',' in the **FROM** Clause and Row Variable References

SELECT …
FROM Q_1 **AS** t_1, Q_2 **AS** t_2, Q_3 **AS** t_3 -- $t_{i<j}$ *not* free in Q_j

---

- Q: Why is $t_{i<j}$ *not* usable in Q_j?

- A: "*… the ',' in FROM is commutative and associative…*".
  Query optimization might rearrange the Q_j:

$$Q_1 \times Q_2 \times Q_3$$
$$\times$$
$$Q_1 \times Q_3 \times Q_2$$
$$\times$$
$$(Q_3 \bowtie Q_1) \times Q_2$$

❶ original order as suggested by FROM clause

❷ swapped Q_2,Q_3 (Q_1,Q_3 now adjacent)

❸ join Q_3,Q_1 first (expect small $|Q_3 \bowtie Q_1|$)
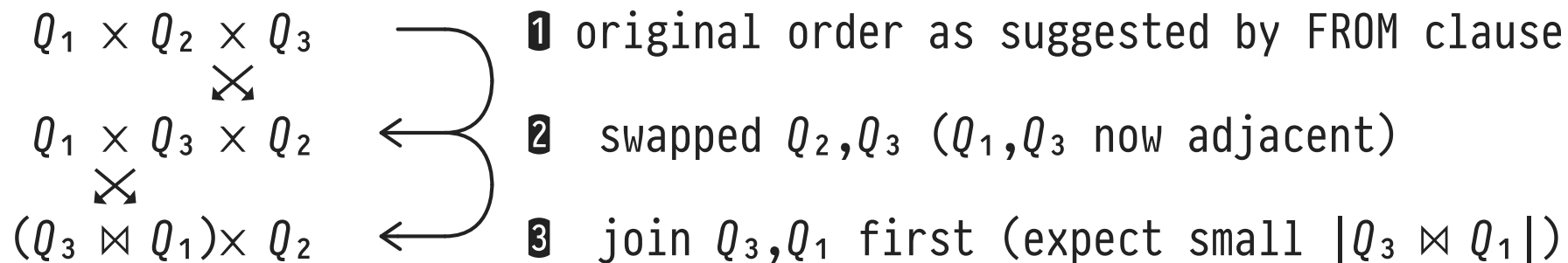
But Dependent Iteration in FROM is Useful...

Recall (find largest label in each tree t_1):

```
SELECT t₁.tree, MAX(t₂.label) AS "largest label"
--         Q₁                    Q₂
--
FROM    Trees AS t₁, unnest(t₁.labels) AS t₂(label)
GROUP BY t₁.tree;
```

- **Dependent iteration** (here: Q_2 depends on t_1 defined in Q_1) has its uses and admits intuitve query formulation.

- $\Rightarrow$ Exception: the arguments of table-generating functions may refer to row variables defined earlier (like t_1).

LATERAL:[6] Dependent Iteration for Everyone

Prefix Q_j with LATERAL in the FROM clause to announce dependent iteration:

```
SELECT …
FROM    Q₁ AS t₁, …, LATERAL Qⱼ AS tⱼ, …
                              ▲
                    may refer to t₁,…,tⱼ₋₁
```

- Works for *any* table-valued SQL expression Q_j, subqueries in (⋯) in particular.
  - Good style: be explicit and use LATERAL even with table functions.

[6] Lateral /ˈlæt(ə)rəl/ a. [Latin lateralis]: *sideways*

LATERAL: SQL's **for each**-Loop

LATERAL admits the formulation of **nested-loops** computation:

```
SELECT e
FROM   Q₁ AS t₁, LATERAL Q₂ AS t₂, LATERAL Q₃ AS t₃
```

is evaluated just like this nested loop:

```
for t₁ in Q₁
  for t₂ in Q₂(t₁)
    for t₃ in Q₃(t₁,t₂)
      return e(t₁,t₂,t₃)
```

- Convenient, intuitive, and perfectly OK.
  But much like hand-cuffs for the query optimizer. ⚠️

LATERAL Example: Find the Top *n* Rows Among a Peer Group

Which are **the three tallest** two- and four-legged dinosaurs?

```
SELECT locomotion.legs, tallest.species, tallest.height
FROM   (VALUES (2), (4)) AS locomotion(legs),
       LATERAL (SELECT d.*
                FROM   dinosaurs AS d
                WHERE  d.legs = locomotion.legs  ⬅
                ORDER BY d.height DESC
                LIMIT 3) AS tallest
```

legs	species	height
2	Tyrannosaurus	7
2	Ceratosaurus	4
2	Spinosaurus	2.4
4	Supersaurus	10
4	Brachiosaurus	7.6
4	Diplodocus	3.6

ACM ICPC Task **Finding Seats** (South American Regionals, 2007)

"K friends go to the movies but they are late for tickets. To sit all nearby, they are looking for K free seats such that the rectangle containing these seats has minimal area."

- Assume *K* = 5:

○ free seat
● occupied seat

⌐ minimal seating area has size 6
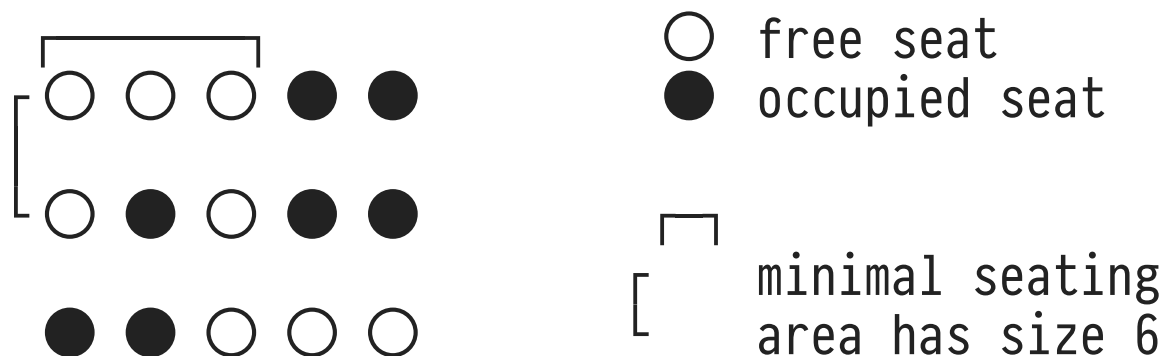
🔧 Finding Seats: Parse the ICPC Input Format

- Typical ICPC character-based input format:

...XX^C_R		. free seat
.X.XX^C_R		X occupied seat
XX...		^C_R new line

- **Parse into table** making seat position/status explicit:

row	col	taken?
1	1	false
1	2	false
1	3	false
1	4	true
⋮	⋮	⋮
3	5	false

Table seats

🔧 Finding Seats: Parse the ICPC Input Format (Table **seats**)

```
\set cinema '...XX\\n.X.XX\\nXX...'

SELECT  row.pos, col.pos, col.x = 'X' AS "taken?"
FROM    -- rows
        unnest(string_to_array(:'cinema', '\n'))
        WITH ORDINALITY AS row(xs, pos),
        -- columns
        LATERAL unnest(string_to_array(row.xs, NULL))
                WITH ORDINALITY AS col(x, pos)
```

- string_to_array(:'cinema', '\n') yields an array of three row strings: {'...XX','.X.XX','XX...'}.
- string_to_array(row.xs, NULL) splits string row.xs into an array of individual characters (= seats).

🔧 **Finding Seats: A Problem Solution (Generate and Test)**

- **Query Plan:**

1. Determine the extent ($rows$ × $cols$) of the cinema seating plan.
2. **Generate all** possible north-west (nw) and south-east (se) corners of rectangular seating areas:
   - For each such ⌐nw,se⌐ rectangle, scan its seats and **test** whether the number of free seats is ⩾ K.
   - If so, record nw together with the rectangle's width/height.
3. Among these rectangles with sufficient seating space, select those with minimal area.

🔧 Finding Seats: Generating All Possible Rectangles

Generate all ⌜*nw*,*se*⌟ corners for rectangles up to maximum size *rows* × *cols*:

```
SELECT ROW(row_nw, col_nw) AS nw,
       ROW(row_se, col_se) AS se
FROM   generate_series(1, rows)              AS row_nw,
       generate_series(1, cols)              AS col_nw,
       LATERAL generate_series(row_nw, rows) AS row_se,
       LATERAL generate_series(col_nw, cols) AS col_se
```

Generates $\left(\sum_{r=1}^{rows} r \right) \times \left(\sum_{c=1}^{cols} c \right)$ rectangles ⇒ test/filter early!