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 $\{x_1,\ldots,x_n\}$.[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!**

- 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

…	A :: κ	…
	α_1	
	α_2	
	α_3	
	α_4	

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

⚠ empty array α_3 absent

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

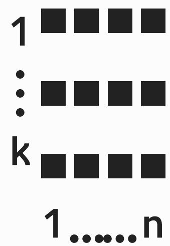
One-dimensional array literals of type τ[]:

array[] :: τ[]	empty array of elements of type τ
array[‹x_1›,…,‹x_n›] '{‹x_1›,…,‹x_n›}' :: τ[]	all x_i of type τ

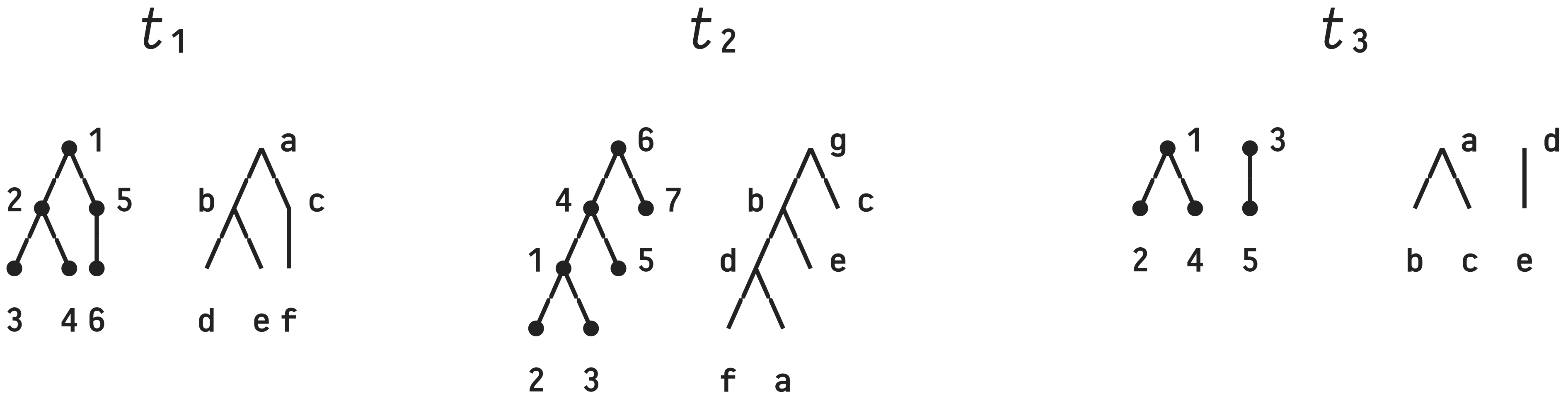
Multi-dimensional rectangular array literals of type τ[][]:

⚠ 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}›}}' :: τ[][]



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



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
- **concatenate** arrays:

```
array_append (array[x₁,…,xₙ],⁜)  ≡  array[x₁,…,xₙ,⁜]
array_prepend(array[x₁,…,xₙ],⁜)  ≡  array[⁜,x₁,…,xₙ]

array_cat(array[x₁,…,xₙ],
          array[y₁,…,yₘ])         ≡  array[x₁,…,xₙ,y₁,…,yₘ]
```

- Overloaded operator || embraces all of the above:

```
xs || ⁜  ≡ array_append(xs, ⁜)
 ⁜ || xs ≡ array_prepend(xs, ⁜)
xs || ys ≡ array_cat(xs,ys)
```

Accessing Arrays: Indexing / Slicing

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

```
    xs[i]     ≡ xᵢ          xs one-dimensional, i ∉ {1,…,n}: NULL
(NULL)[i]     ≡ NULL
    xs[NULL]  ≡ NULL
    xs[i:j]   ≡ array[xᵢ,…,xⱼ]                        i > j: array[]
    xs[i: ]   ≡ array[xᵢ,…,xₙ]
    xs[ :j]   ≡ array[x₁,…,xⱼ]
```

- Access **last element** x_n:

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

 ∑ (# of elements) in all dimensions
```

Searching for Elements in Arrays

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

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

$$x\ \theta\ \mathrm{ANY}(xs) \equiv \exists\, i\in\{1,\cdots,n\}\colon x\ \theta\ xs[i]$$

$$x\ \theta\ \mathrm{ALL}(xs) \equiv \forall\, i\in\{1,\cdots,n\}\colon x\ \theta\ xs[i]$$

$$\texttt{array\_position}(xs,※) \equiv i \qquad \text{if ※ not found: NULL}$$

$$\texttt{array\_positions}(xs,※) \equiv \texttt{array}[i,j] \qquad \text{if ※ not found: array[]}$$

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

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

$\underbrace{\texttt{array}[x_1,\ldots,x_n]}_{\equiv\ xs}$ $\equiv$

elem
x_1
$\vdots$
x_n

Table t

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

$\equiv$

xs
$\{x_1,\ldots,x_n\}$

- 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[x_1,…,x_n])
       WITH ORDINALITY AS t(elem,idx)
```

≡

elem	idx
x_1	1
⋮	⋮
x_n	n

recall ordered aggregates

```
SELECT array_agg(t.elem ORDER BY t.idx) AS xs
FROM   (VALUES (x_1,1),
                 ⋮
               (x_n,n)) AS t(elem,idx)
```

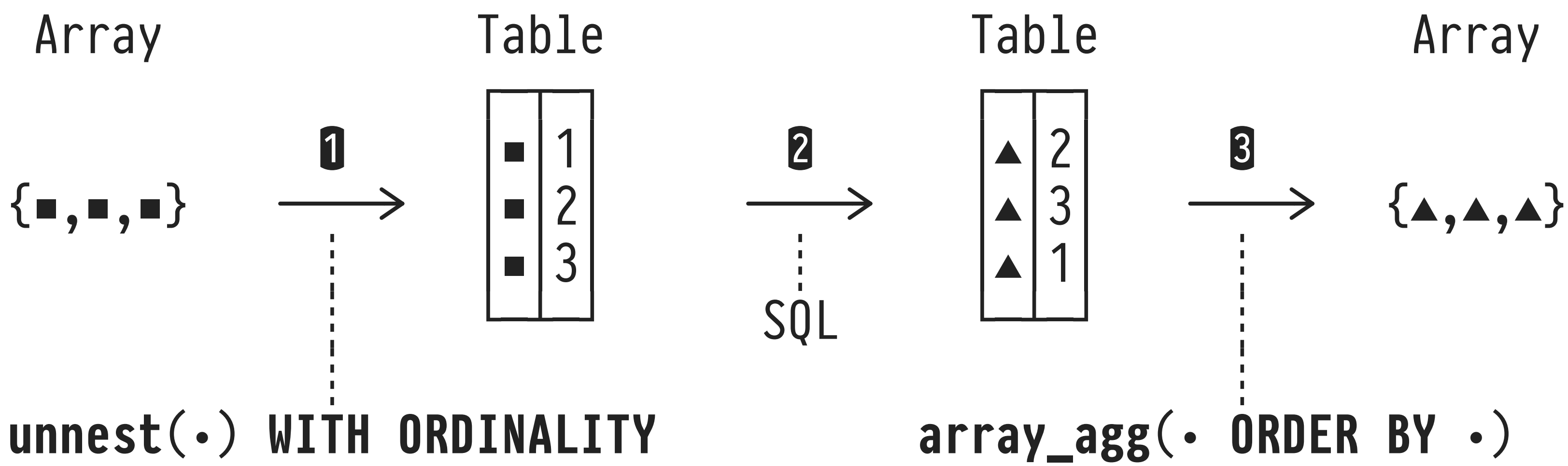
≡

xs
$\{x_1,…,x_n\}$

- ‹f›(…) WITH ORDINALITY adds a trailing column (☗) of ascending indices 1,2,… to the output of function f.

A Relational Array Programming Pattern

Availability of unnest(•) and ordered array_agg(•) 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]

$$\text{unnest} :: \tau[\,] \rightarrow \text{SETOF } \tau$$

- In SQL, functions of type $\tau_1 \rightarrow \text{SETOF } \tau_2$ 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
	⋮
⩽ t ➨	f+n×s

⟨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 i^{th} *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);
```

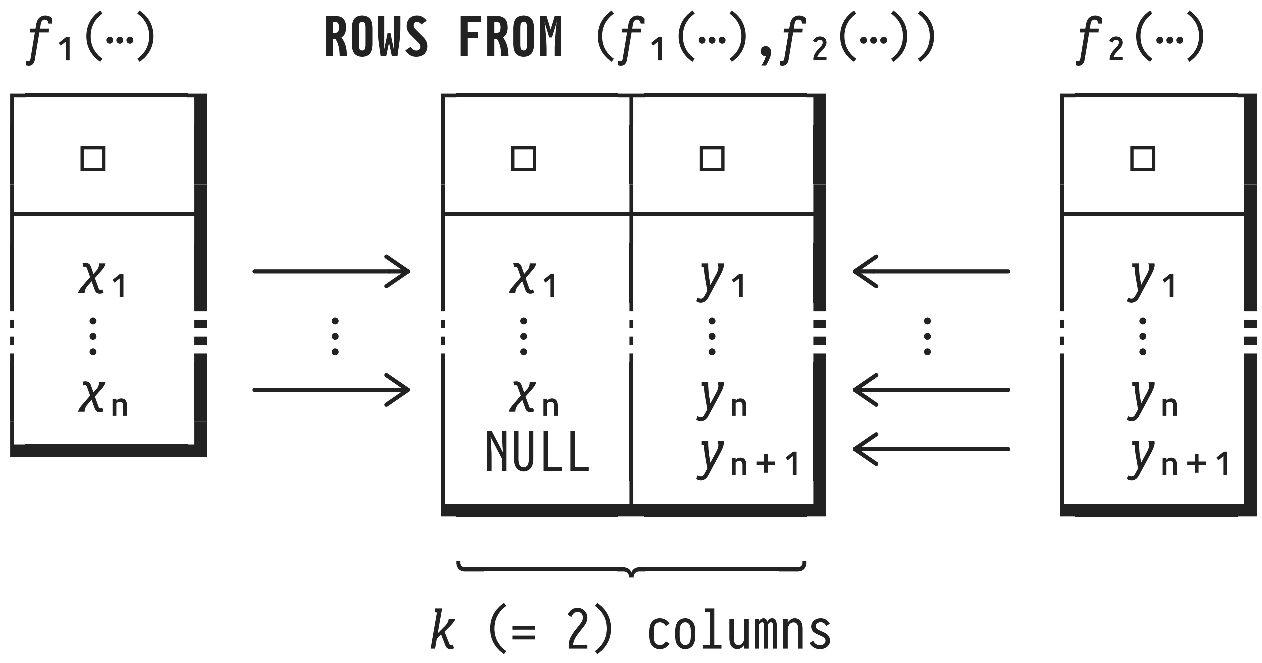
element	# atoms	charge
C	$_6$	NULL
H	$_5$	NULL
O	$_7$	$^{3-}$

NULL ≡ no match

Zipping Arrays and Table-Generating Functions

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

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



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 q_i 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 $\tau_1 \times \cdots \times \tau_k \to \tau$.
  - **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:

$$f_1 :: \overbrace{\text{anyelement} \times \text{anyelement}}^{=} \to \text{boolean}$$

$$f_2 :: \underbrace{\text{anyarray} \times \text{integer} \to \text{anyelement}}_{\text{elem} =}$$

UDFs Can Return Tables

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

	atomic τ	τ ≡ SETOF τ'
If q_n[4] returns no rows, If q_n returns rows, May be invoked	returns NULL returns the first row wherever v::τ is used	returns empty table returns all rows 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***...ϟ)
  - No IMMUTABLE option—use VOLATILE instead.
  - Use τ ≡ void if f is all about side-effects or consider adding … RETURNING ‹e_1›,…,‹e_m› if $i = n$.

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

Example UDF: Map Unicode Subscripts

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

```
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.

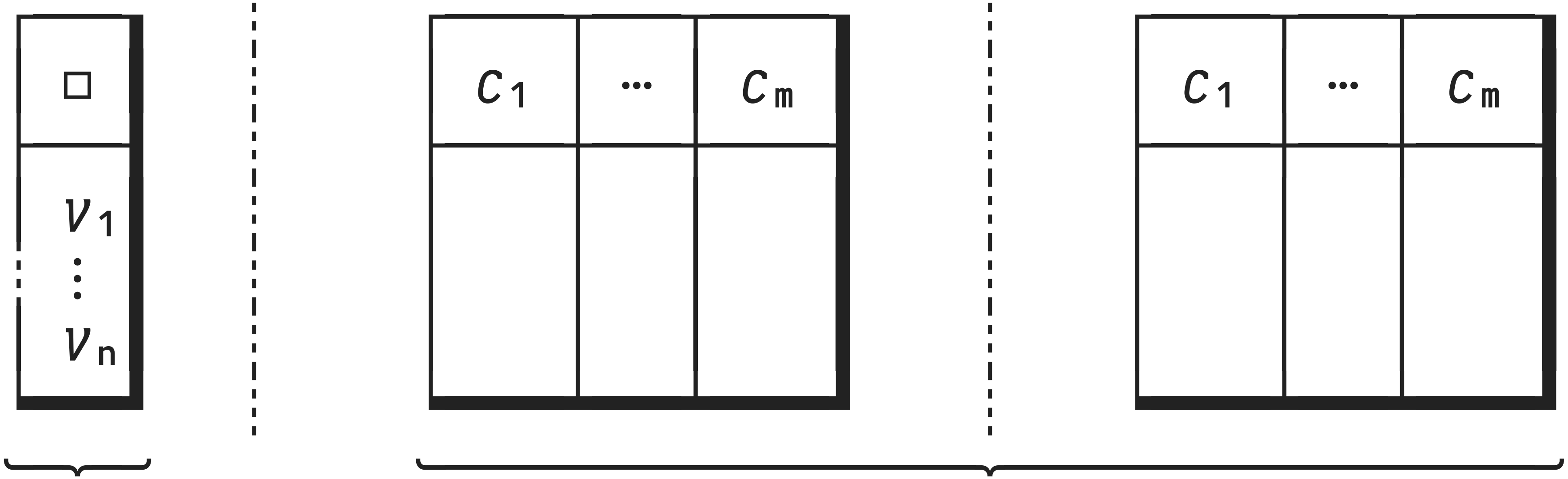
[5] Built-in function unnest(•) can flatten *n*-dimensional arrays in row-major order.

Table-Generating UDFs: Returning Typed Rows

Assume a table-generating UDF f :: … → τ.

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:

$$Q_1 \times Q_2 \times Q_3$$

$$Q_1 \times Q_3 \times Q_2$$

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

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.
- ⇒ 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 Q_1 **AS** t_1, **LATERAL** Q_2 **AS** t_2, **LATERAL** Q_3 **AS** t_3

is evaluated just like this nested loop:

for t_1 in Q_1
  for t_2 in $Q_2(t_1)$
    for t_3 in $Q_3(t_1,t_2)$
      return $e(t_1,t_2,t_3)$

- 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?

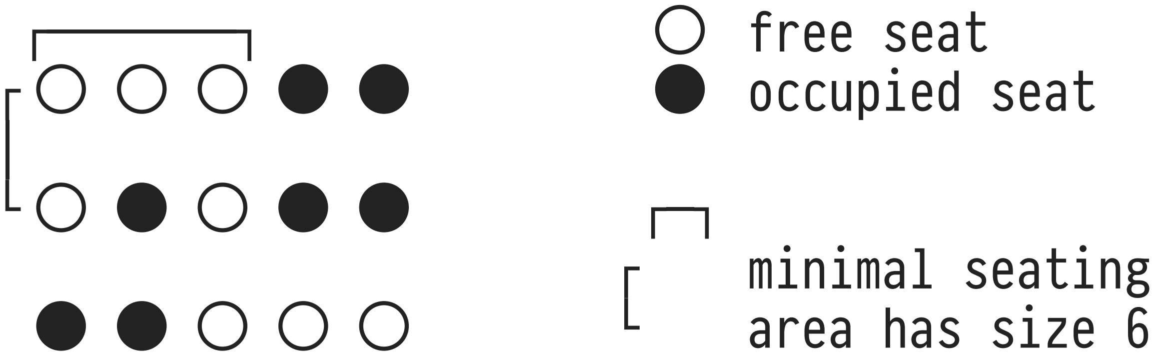
```
SELECT locomotion.legs, tallest.species, tallest.height
FROM   (VALUES (2), (4)) AS locomotion(legs),
       LATERAL (SELECT d.*
                FROM   dinosaurs AS d
                WHERE  d.legs = locomotion.legs
                ORDER BY d.height DESC
                LIMIT 3) AS tallest
```

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 $K = 5$:



Finding Seats: Parse the ICPC Input Format

- Typical ICPC character-based input format:

```
...XX␍        .  free seat
.X.XX␍        X  occupied seat
XX...         ␍  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 ($rows \times cols$) 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 $\geqslant K$.
     - 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!