Advanced SQL

03 — Arrays and User-Defined Functions

Torsten Grust
Universität Tübingen, Germany

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 $\{x_1,\dots,x_n\}$.[1]
- SQL treats v as an atomic unit, but …
- … array functions and operators also enable SQL to query the x_i individually (there's some ϟ with 1NF here).

[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.)

T

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

“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.

3 ┆ Array Literals

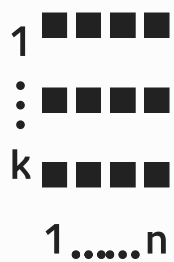
One-dimensional array literals of type τ[]:

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

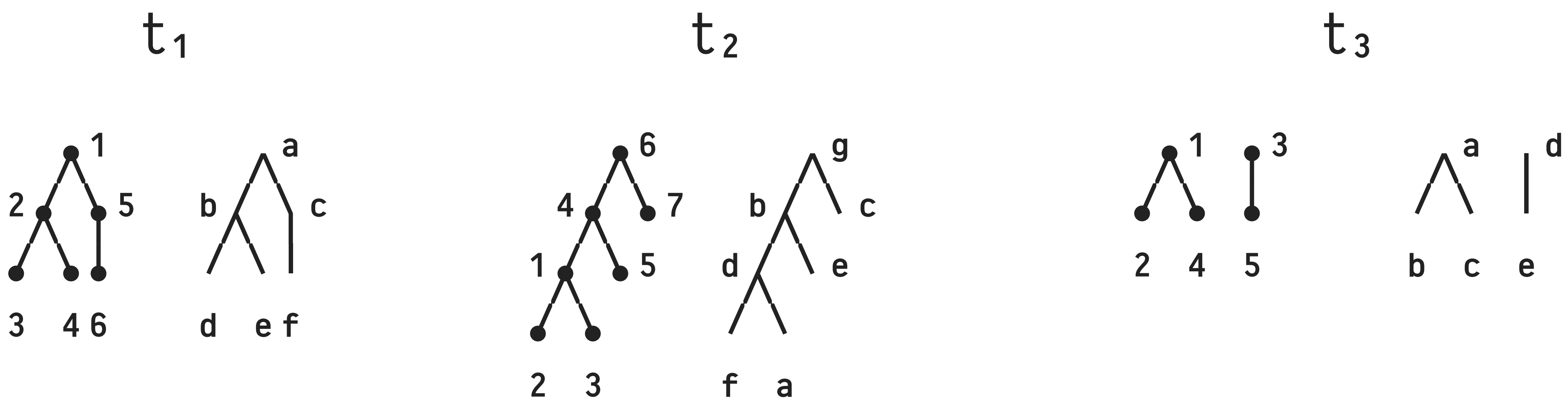
Multi-dimensional rectangular array literals of type τ[][]:

⚠️ 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:

Trees

tree	parents	labels
t_1	{NULL,1,2,2,1,5}	{'a','b','d','e','c','f'}
t_2	{4,1,1,6,5,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

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 $xs \equiv \text{array}[x_1,\ldots,x_n]$):

```
    xs[i]      ≡ x_i                     i ∉ {1,…,n}: NULL
(NULL)[i]      ≡ NULL
    xs[NULL]   ≡ NULL
    xs[i:j]    ≡ array[x_i,…,x_j]        i > j: array[]
    xs[i: ]    ≡ array[x_i,…,x_n]      ⎱ ⚠ requires
    xs[ :j]    ≡ array[x_1,…,x_j]      ⎰ PostgreSQL 9.6
```

- 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. Instead, **searching** accesses arrays by **contents**.

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

```
x θ ANY(xs)              ≡ ∃ i∈{1,⋯,n}: x θ xs[i]
x θ ALL(xs)              ≡ ∀ i∈{1,⋯,n}: x θ xs[i]

array_position(xs,★)  ≡ i            if ★ not found: NULL
array_positions(xs,★) ≡ array[i,j]   if ★ not found: array[]

array_replace(xs,★,⬟) ≡ array[x₁,…,⬟,…,⬟,…,xₙ]
                                    i   j
```

```
SELECT t.elem
FROM   unnest(array[x_1,…,x_n]) AS t(elem)
```

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

≡

Table t

elem
x_1 ⋮ x_n

```
SELECT array_agg(t.elem) AS xs
FROM   (VALUES (x_1),
                 ⋮
               (x_n)) AS t(elem)
```

≡

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)
```

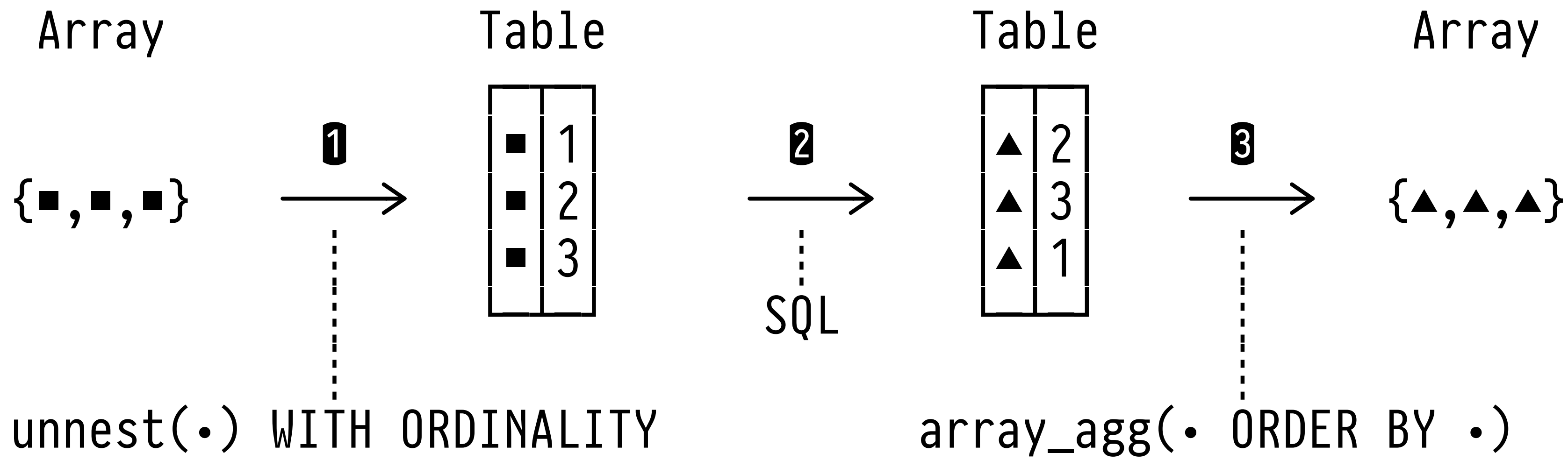
≡

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.

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 — 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› ➨ ‹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., $C_6H_5O_7^{3-}$) ✎

```sql
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);
```

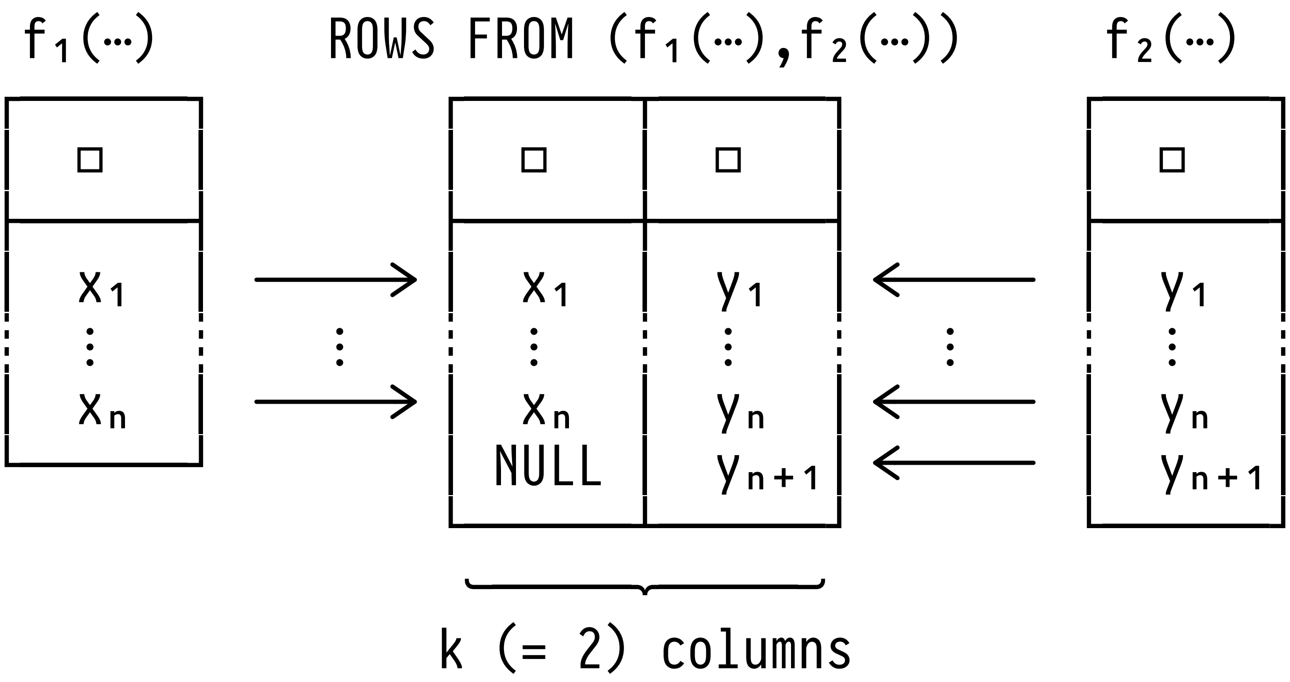
element	# atoms	charge
C	$_6$	NULL
H	$_5$	NULL
O	$_7$	$^{3-}$

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(…),…,f_k(…))
- Zipping arrays xs_i: unnest(xs_1,xs_2,…,xs_k)



The body of a **user-defined SQL function (UDFs)** evaluates $n \geq 1$ 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 $\langle f \rangle$ 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 $(\langle f \rangle, \tau_1, \ldots, \tau_k)$ 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:

```
                  =
f1 :: anyelement × anyelement → boolean
f2 :: anyarray × integer → anyelement
                    elem =
```

UDFs Can Return Tables

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

Regular vs. Table-generating UDFs

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

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

[4] Recall: $\langle f \rangle$'s body evaluates queries $\langle q_1 \rangle, \ldots, \langle q_n \rangle$ (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:

```
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
```

Table issue

id :: serial	when
⋮	⋮
42	2017-05-17 14:25:36.928441
⋮	⋮

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.

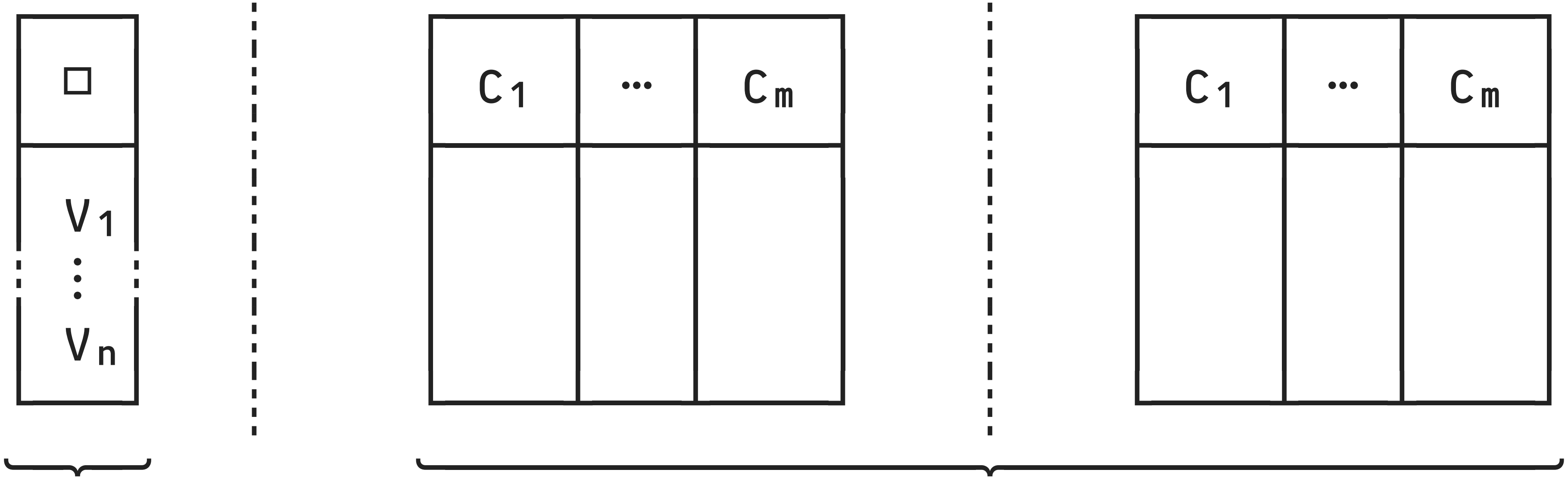
[5] Built-in function unnest(·) can flatten *n*-dimensional arrays in row-major order.

Table-Generating UDFs: Returning Typed Rows

Assume a table-generating UDF $\langle f \rangle :: \cdots \to \tau$.

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   Q₁ AS t₁, Q₂ AS t₂, Q₃ AS t₃ -- 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:

$Q_1 \times Q_2 \times Q_3$ ❶ original order as suggested by FROM clause

$Q_1 \times Q_3 \times Q_2$ ❷ swapped Q_2, Q_3 (Q_1, Q_3 now adjacent)

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

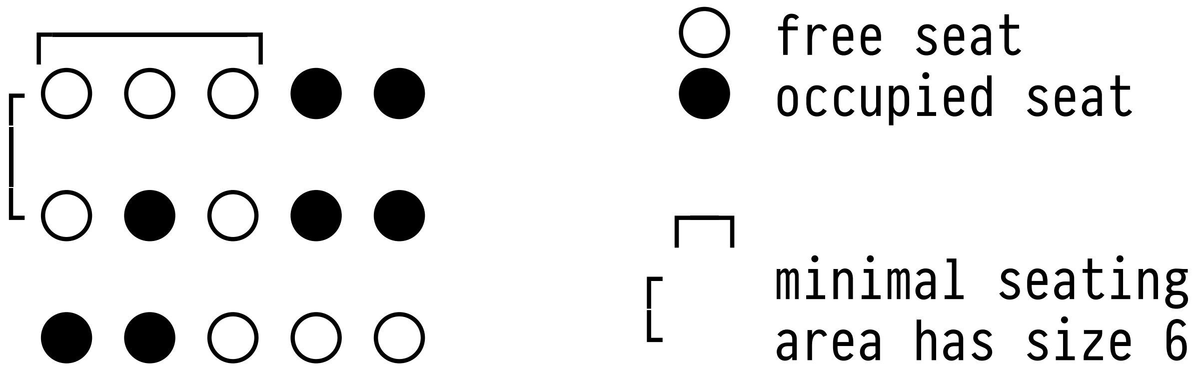
```
SELECT locomotion.legs, tallest.species, tallest.height
FROM   (VALUES (2), (4)) AS locomotion(legs),
       LATERAL (SELECT d.*
                FROM   dinosaurs AS d
                WHERE  d.legs = locomotion.legs
                ORDER BY d.height DESC
                LIMIT 3) AS tallest
```

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 $K = 5$:



Finding Seats: Parse the ICPC Input Format

- Typical ICPC character-based input format:

```
...XX␍
.X.XX␍
XX...
```

.	free seat
X	occupied seat
␍	new line

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

Table seats

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

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!