Processing Data in its Own Habitat

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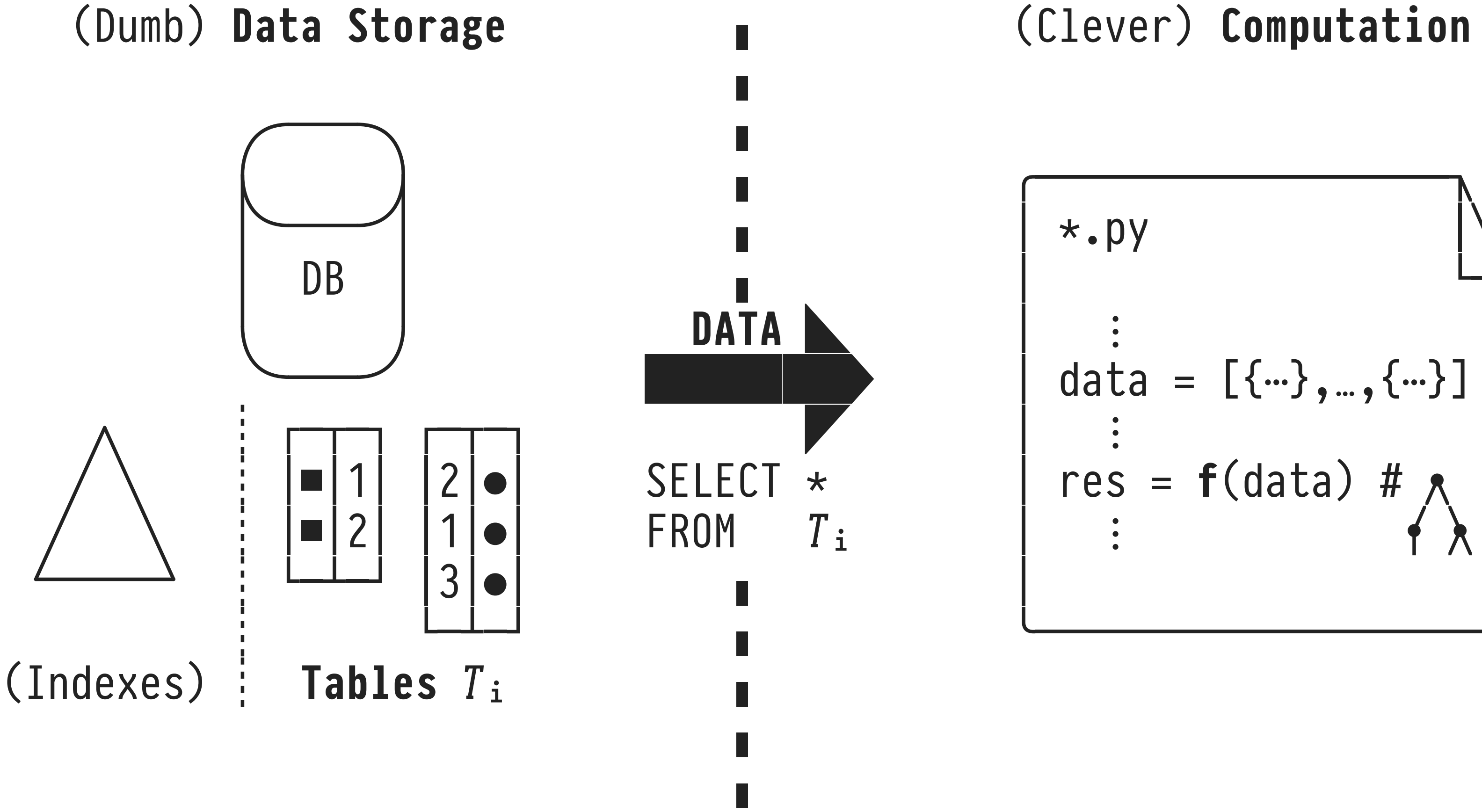
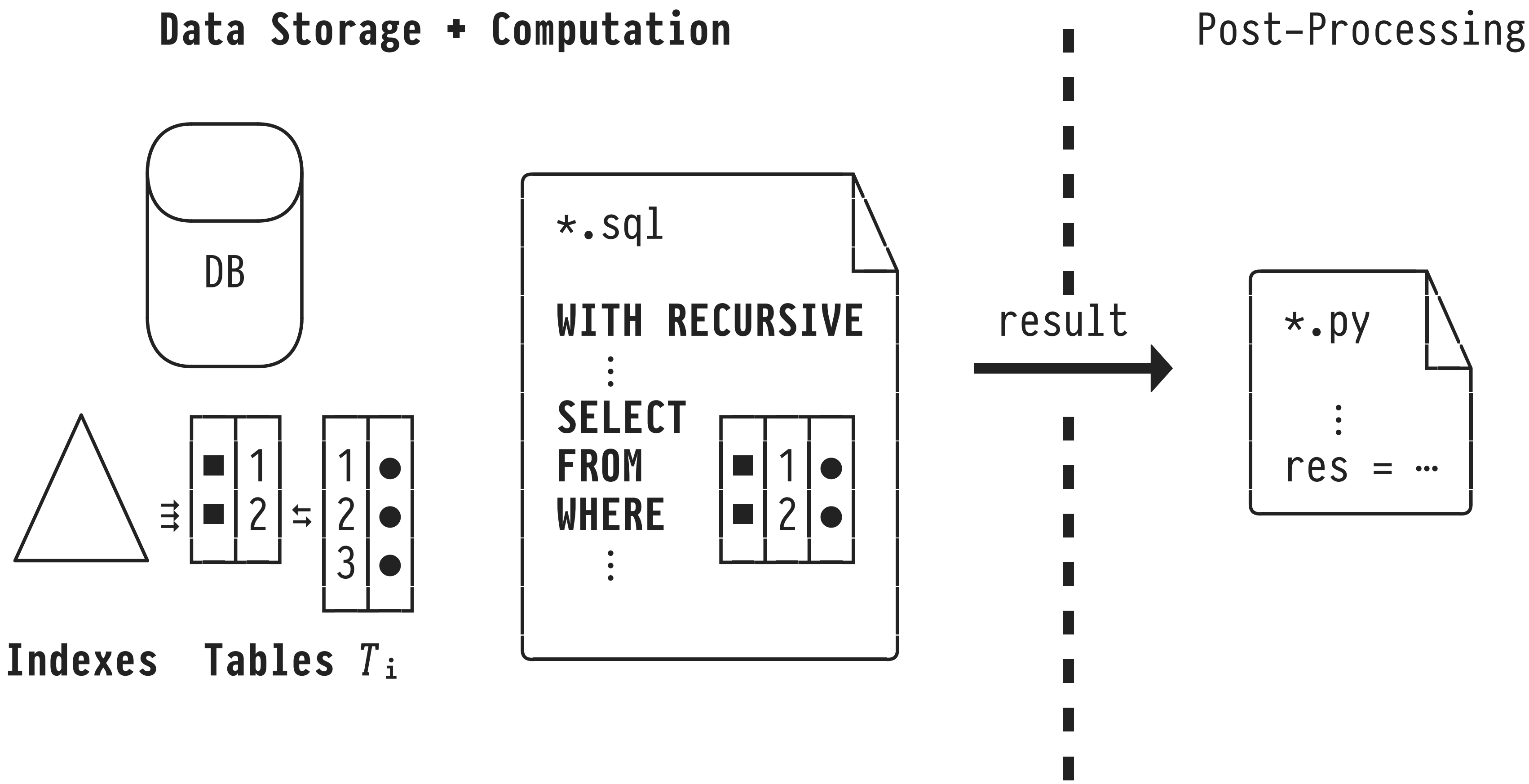
“First off, release the data from its relational jail.”



“Move your computation close to the data,” says Stonebraker



SQL Has Moved on Since SQL:1992

SQL Clauses and Expressions (as of SQL:2016)		
	⋮	⋮
"New" SQL	**WITH RECURSIVE**	*letrec*, iteration
	MATCH_RECOGNIZE	row pattern matching
	ROWS FROM	*zip*
	UDFs (SQL, procedural)	user-def'd functions
	WINDOW (**OVER**(…))	*scan*, …
	array_agg, unnest [**WITH ORDINALITY**]	array processing
	multisets, row values, enums	non-scalar table cells
	mode(), …, **FILTER**, **WITHIN GROUP**	filtered/ordered agg's
	WITH	*let*
	CASE…**WHEN**…**ELSE**…**END**	*if*…*then*…*else*
	LATERAL	[…| x ← xs, y ← f(x)]
Old SQL	**SELECT**…**FROM**…**WHERE**	join, selection, projection
	GROUP BY…**HAVING**	grouping/aggregation
	ORDER BY	ordering (cosmetic)

> "*SQL, Lisp, and Haskell are the only programming languages that I've seen where one spends more time thinking than typing.*"
>
> —Philip Greenspun

[1] Let me add APL to that list.

Recursion

But Can I Do That Using SQL? — You Sure Can.

The addition of **recursion** to SQL:1999 changes everything:

Expressiveness SQL becomes a **Turing-complete language** and thus—in principle—a general-purpose PL (albeit with a particular flavor).

Efficiency ⚠️ **No longer** are queries guaranteed to **terminate** or to be **evaluated with polynomial effort.**

Like a pact with the 👿 — but the payoff is plenty.

Shape of a Recursive SQL Query

```
WITH RECURSIVE
  T(…) AS (
      q_0              -- base case query, evaluated once

    UNION [ ALL ]
                       -- recursive query refers to T itself,
      q↺(T)            --   evaluated repeatedly
  )
q_1(T)                 -- final post-processing query
```

- (Almost the) Semantics in a nutshell:

$$q_1(\underbrace{q_{\circlearrowleft}(\cdots q_{\circlearrowleft}(q_{\circlearrowleft}(q_0))\cdots) \cup \cdots \cup q_{\circlearrowleft}(q_{\circlearrowleft}(q_0)) \cup q_{\circlearrowleft}(q_0)}_{\text{repeated evaluation of } q_{\circlearrowleft} \text{ (when to stop?)}} \cup q_0)$$

Semantics of a Recursive SQL Query (**UNION ALL** Variant)

Iterative and recursive semantics—both are equivalent:

<pre>iterate(q⟲, q0):
  r ← q0
  t ← r
  while t ≠ ∅
  │ t ← q⟲(t)
  └ r ← r ⊎ t
  return r</pre>
	<pre>recurse(q⟲, r):
	  if r ≠ ∅ **then**
	  │ **return** r ⊎ recurse^all(q⟲, q⟲(r))
	  else
	  └ **return** ∅</pre>

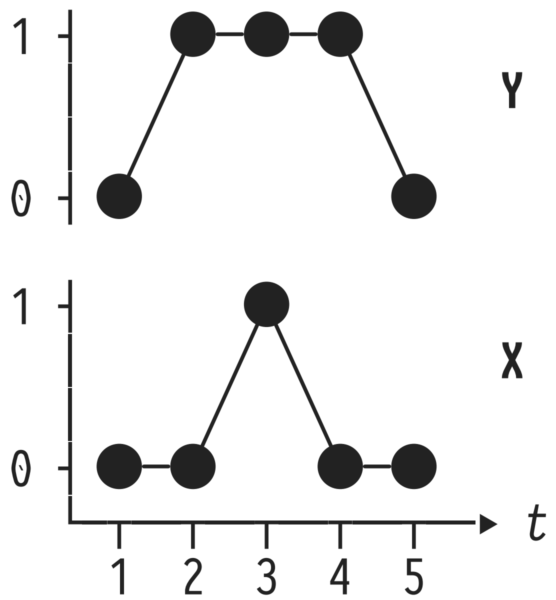
- Invoke the recursive variant via recurse(q⟲, q_0).
- Recursive query q⟲ sees *all rows added in the last iteration/recursive call*. Exit if no rows added.
- Could **immediately emit t** — no need to build r.

X

t	*val*
1	0
2	0
3	1
4	0
5	0

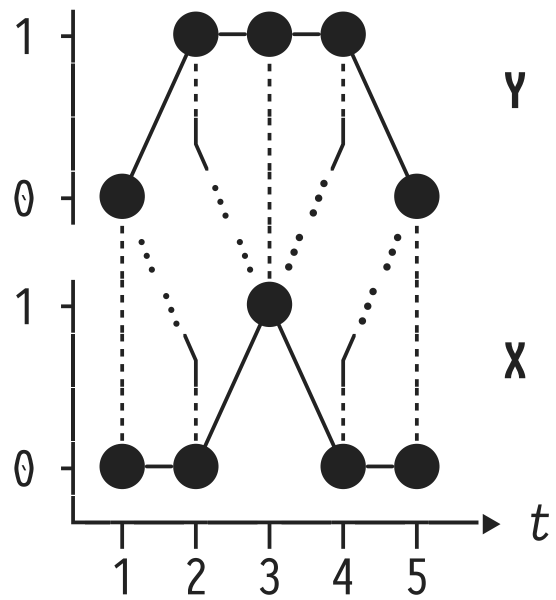
Y

t	*val*
1	0
2	1
3	1
4	1
5	0



Dynamic Time-Warping Distance (DTW)

Stretch/compress series **X** = (x_i) and **Y** = (y_j) along the time axis to align both optimally:



Q: DTW — Hand-Crafted SQL Code (Not in Any Textbook…)

```
WITH RECURSIVE matrix(i,j,val) AS (
    (SELECT X.t, Y.t, abs(X.val - Y.val)
     FROM   X, Y
     ORDER BY X.t, Y.t
     LIMIT 1)

  UNION

⋆   SELECT step.i, step.j, MIN(step.val)
    FROM (SELECT step.i, step.j, m.val + step.val
          FROM   matrix AS m,
                 (VALUES (1,1), (0,1), (1,0)) AS Δ(i,j),
                 LATERAL (
                   SELECT m.i+Δ.i, m.j+Δ.j, abs(X.val - Y.val)
                   FROM X, Y
                   WHERE (X.t,Y.t) = (m.i+Δ.i,m.j+Δ.j)) AS step(i,j,val)
          WHERE (step.i,step.j) <= (i,j)
⋆        ) AS step(i,j,val)
⋆   GROUP BY step.i, step.j                                  --
  )                                                          --
  SELECT MIN(m.val) AS dtw                                   -- with (i,j) = (5,5):
  FROM   matrix AS m                                         --
  WHERE  (m.i,m.j) = (i,j);                                  -- ⌛ ≈ 3ms
```

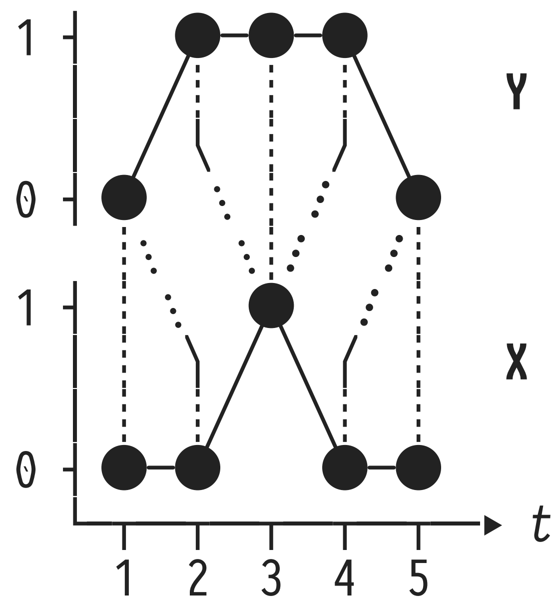
dtw
0.0

Q: DTW — Textbook Recursive Algorithm

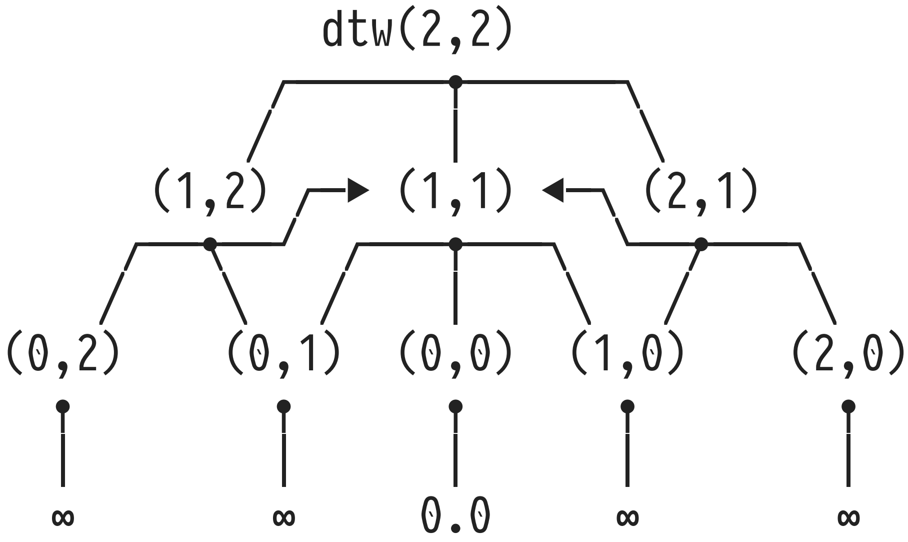
$$\mathrm{dtw}(0, 0) = 0.0$$
$$\mathrm{dtw}(i, 0) = \infty$$
$$\mathrm{dtw}(0, j) = \infty$$
$$\mathrm{dtw}(i, j) = |x_i - y_j| + \min \begin{Bmatrix} \mathrm{dtw}(i-1, j-1) \\ \mathrm{dtw}(i-1, j\ \ ) \\ \mathrm{dtw}(i\ \ , j-1) \end{Bmatrix} \quad \begin{matrix} \text{-- match} \\ \text{-- stretch} \\ \text{-- compress} \end{matrix}$$

Matrix
dtw(i,j)

$$\begin{array}{cc} & \\ j & \begin{array}{c} 5 \\ 4 \\ 3 \\ 2 \\ 1 \end{array} \end{array} \begin{array}{c} \begin{pmatrix} 3 & 3 & 1 & 0 & \mathbf{0} \\ 3 & 3 & 0 & 1 & 2 \\ 2 & 2 & 0 & 1 & 2 \\ 1 & 1 & 0 & 1 & 2 \\ 0 & 0 & 1 & 1 & 1 \end{pmatrix} \\ \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\ i \end{array}$$



Phase ❶: Resulting Call Graph



- Table **call_graph** encodes dtw(·,·)'s call *graph*.
- Compute each missing result ▢ once, bottom-up
  ⇛ realizes sharing during evaluation.

Table **call_graph**

(i,j)	**site**	**(i↗,j↗)**	**result**
(2,2)	❶	(1,1)	▢
(2,2)	❷	(1,2)	▢
(2,2)	❸	(2,1)	▢
(1,1)	❶	(0,0)	▢
(1,1)	❷	(0,1)	▢
(1,1)	❸	(1,0)	▢
(1,2)	❶	(0,1)	▢
(1,2)	❷	(0,2)	▢
(1,2)	❸	(1,1)	▢
⋮	⋮	⋮	⋮
(0,0)	▢	▢	0.0
(0,1)	▢	▢	∞
(1,0)	▢	▢	∞
(0,2)	▢	▢	∞
(2,0)	▢	▢	∞

Phase ❷: Final Result of Evaluation

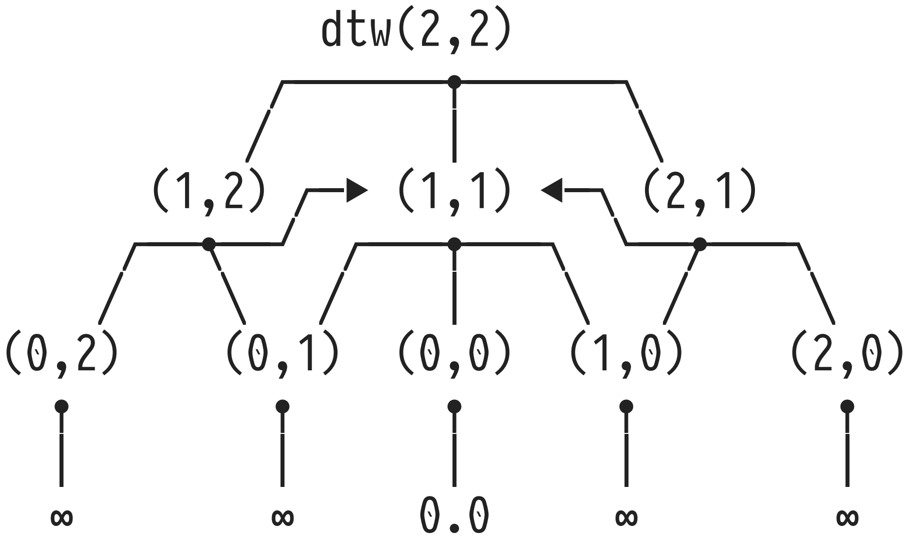


Table **evaluation**

(i,j)	result
(2,2)	1
(2,1)	0
(1,1)	0
(1,2)	1
(2,0)	∞
(1,0)	∞
(0,2)	∞
(0,1)	∞
(0,0)	0

- Column result of row (i,j) = (2,2) holds function call result.
- Hold on to table evaluation to **memoize** function dtw(·,·).

Write SQL UDFs in Functional Style!

- Compilation of “functional-style” SQL UDFs into recursive CTEs can come close to hand-crafted CTEs:

DTW Variant	⌛ Wall-Clock Time for *dtw(5,5)*
Hand-crafted Recursive CTE	3 ms
Recursive SQL UDF (native)	≈1100 ms
Recursive SQL UDF (compiled into CTE)	15 ms

- Opportunities:
  1. **Memoization:** keep table evaluation (STABLE UDFs: within transaction, IMMUTABLE UDFs: across transactions).
  2. **Parallelization:** chop call graph, evaluate sub-graphs in ∥.

Process Your Data in its Own Habitat!

> *Move your computation close to the data. [paraphrased]*
>
> —Mike Stonebraker

More Application/Algorithms Expressed in SQL
Barnes-Hut *n*-body simulation
CASH algorithm (robust clustering)
Cellular automata (*Game-of-Life*-style)
CYK parsing
Distance vector routing
Graph algorithms (shortest paths, connected components, …)
Handwriting recognition
Liquid/heat flow simulations, water percolation
Loose index scans
Markov decision processes (robot control)
Spreadsheet-style formula evaluation
Traffic simulation
Turing machine simulation
Sessionization, bin fitting
Z-order image processing