DB 2

13 – Plan Evaluation

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Evaluating Query Plan Trees

The evaluation of a (complex) query plan requires a coordinated execution of the plan's operators:

- Is data **pushed** from the leaves (*e.g.*, Seq Scan, Index Scan) towards the plan root?
- Or does an operator **pull** the intermediate results from its upstream child operators?
- What kind of data flows across the plan's edges? **Entire tables or columns**? **Single rows**?
- Does the plan execute in one shot or can we **demand** the “next result row” when we are ready to consume it?
    - Can operators remember/resume from their current state?

Query Q_{12} and its (Moderately Complex) Plan

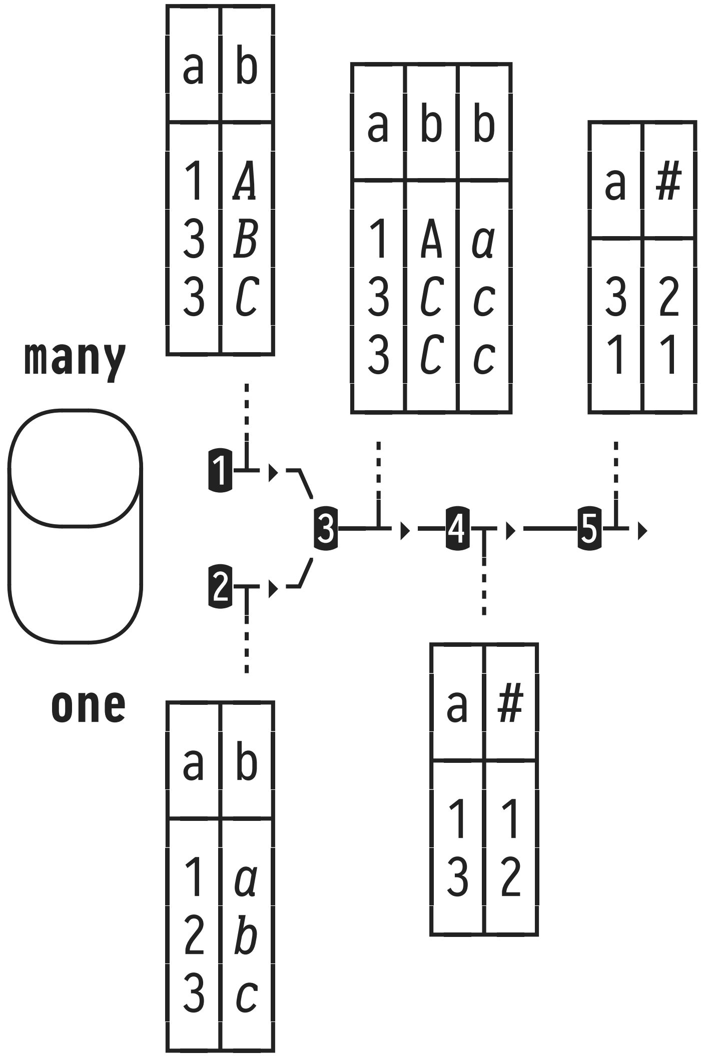
- Q_{12}:

```
SELECT o.a, COUNT(*) AS "#"
FROM   one AS o, many AS m
WHERE  o.a = m.a
GROUP BY o.a
ORDER BY o.a DESC
```

- Plan operators:

❶ Seq Scan on **many** (outer of ❸)
❷ Seq Scan on **one** (inner of ❸)
❸ Nested Loop (Join Filter: o.a = m.a)
❹ HashAggregate (Group Key: o.a)
❺ Sort (Sort Key: o.a DESC)

─▸─ ≡ direction of data flow
❶…❺ ≡ evaluation order



MonetDB: Full Materialization

MonetDB generates MAL programs that evaluate operators following a post-order traversal[1] of the query plan tree.

- Leaf nodes evaluated first, downstream nodes consume BATs generated by child nodes. Root operator evaluated last.
- Each operator consumes entire BATs, generates and **fully materializes** its result BAT(s) [cf. previous slide].
  - 👍 Tight code loops process entire columns. **Instruction *and* data locality**, predictable memory access.
  - 👎 **Size of intermediate results** may exceed available RAM ⇒ OS-level paging and thus disk I/O.

[1] Recall: data-flow dependency analysis enables the // evaluation of ❶ and ❷.

MonetDB: Demonstrate that order of MAL operation follows a leaf-to-root (bottom-up, post-order) traversal of the plan tree. Display intermediate result BATs along the way.

```
-- ❶ Check input tables

  \d one
CREATE TABLE "sys"."one" (
  "a" INTEGER       NOT NULL,
  "b" CHARACTER LARGE OBJECT,
  CONSTRAINT "one_a_pkey" PRIMARY KEY ("a")
);

  \d many
CREATE TABLE "sys"."many" (
  "a" INTEGER       NOT NULL,
  "b" CHARACTER LARGE OBJECT
);

  SELECT * FROM one;
+------+------+
| a    | b    |
+======+======+
|    3 | a    |
|    4 | b    |
|    7 | c    |
|    2 | d    |
|    0 | e    |
|    1 | f    |
|    6 | g    |
|    5 | h    |
+------+------+

  SELECT * FROM many;
+------+------+
| a    | b    |
+======+======+
|    5 | H    |
|    5 | H    |
|    3 | A    |
|    2 | D    |
|    0 | E    |
|    2 | D    |
+------+------+


-- ❷ Query plan for Q₁₂
```

```
  PLAN
    SELECT o.a, COUNT(*) AS "#"
    FROM   one AS o, many AS m
    WHERE  o.a = m.a
    GROUP BY o.a
    ORDER BY o.a DESC;
+-----------------------------------------------------------------------------------------------------+
| rel                                                                                                 |
+=====================================================================================================+
| project ( ⬅ projection & sorting                                                                    |
| | group by (                            table one is build table in (radix-cluster) hash join       |
| | | join (                                        ⬇                                                 |
| | | | table(sys.one) [ "one"."a" NOT NULL HASHCOL  as "o"."a" ] COUNT ,                             |
| | | | table(sys.many) [ "many"."a" NOT NULL as "m"."a" ] COUNT                                      |
| | | ) [ "o"."a" NOT NULL HASHCOL  = "m"."a" NOT NULL ]                                              |
| | ) [ "o"."a" NOT NULL HASHCOL  ] [ "o"."a" NOT NULL HASHCOL , sys.count() NOT NULL as "L3"."L3" ]  |
| ) [ "o"."a" NOT NULL, "L3" NOT NULL as "L4"."#" ] [ "o"."a" NOT NULL ]                              |
+-----------------------------------------------------------------⬆-----------------------------------+
                                             sort criterion (DESC is implicit [ASC would be displayed])


-- ❸ MAL code for Q₁₂ (follow post-order traversal ov above plan tree, column BATs one.b/many.b never accessed)

  EXPLAIN
    SELECT o.a, COUNT(*) AS "#"
    FROM   one AS o, many AS m
    WHERE  o.a = m.a
    GROUP BY o.a
    ORDER BY o.a DESC;
[...]
  X_4 := sql.mvc();

  C_5:bat[:oid] := sql.tid(X_4, "sys", "one");                                   }
  X_8:bat[:int] := sql.bind(X_4, "sys", "one", "a", 0:int);                       } ❶ Scan one.a
  X_17 := algebra.projection(C_5, X_8);                                           }

  C_18:bat[:oid] := sql.tid(X_4, "sys", "many");                                  }
  X_20:bat[:int] := sql.bind(X_4, "sys", "many", "a", 0:int);                     } ❷ Scan many.a
  X_25 := algebra.projection(C_18, X_20);                                         }

  (X_26, X_27) := algebra.join(X_17, X_25, nil:BAT, nil:BAT, false, nil:lng);  } ❸ (Hash) Equi-Join
  X_32 := algebra.projection(X_26, X_17);                                         }

  (X_34, C_35, X_36) := group.groupdone(X_32);                                    }
  X_37 := algebra.projection(C_35, X_32);                                         } ❹ Group + Agg
  X_38:bat[:lng] := aggr.subcount(X_34, X_34, C_35, false);                       }
```

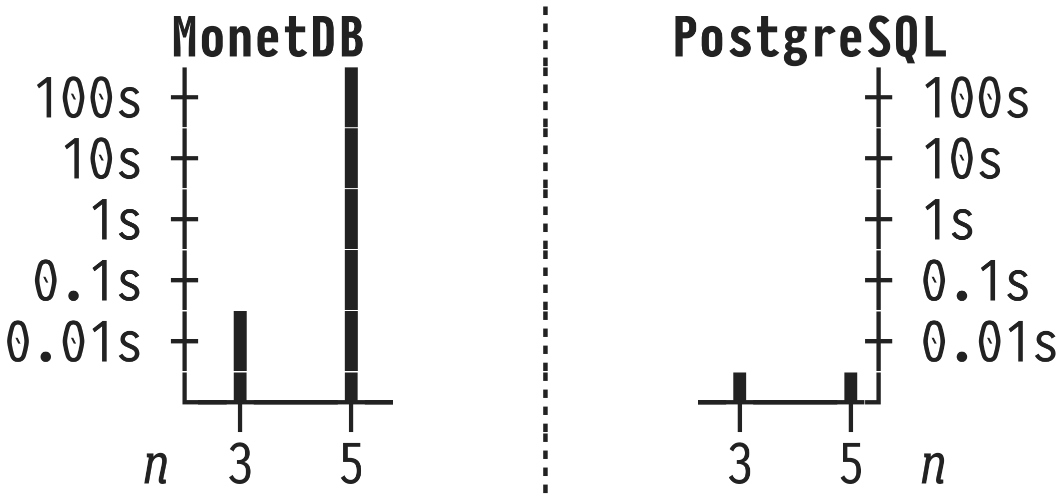
```
  (X_39, X_40, X_41) := algebra.sort(X_37, true, false);                      ⎫ ❺ Sort
  X_44 := algebra.projection(X_40, X_38);                                     ⎭
  X_43 := algebra.projection(X_40, X_37);
[...]


-- ❹ Readable and executable MAL code:

  sql.init();
  sql := sql.mvc();

  # ❶ Scan one.a
  one    :bat[:oid] := sql.tid(sql, "sys", "one");
  one_a0 :bat[:int] := sql.bind(sql, "sys", "one", "a", 0:int);
  one_a  :bat[:int] := algebra.projection(one, one_a0);
  io.print(one_a);

  # ❷ Scan many.a
  many   :bat[:oid] := sql.tid(sql, "sys", "many");
  many_a0:bat[:int] := sql.bind(sql, "sys", "many", "a", 0:int);
  many_a :bat[:int] := algebra.projection(many, many_a0);
  io.print(many_a);

  # ❸ (Hash) Equi-Join      no candidate lists ↴        ↴  no outer ↴     ↲ no result size estimate
  (left, right) := algebra.join(one_a, many_a, nil:bat, nil:bat, false, nil:lng);
  joined_one_a:bat[:int] := algebra.projection(left, one_a);
  io.print(joined_one_a);

  # ❹ Group + Agg
  (grouped_one_a, group_keys, group_sizes) := group.groupdone(joined_one_a);
  keys_a:bat[:int] := algebra.projection(group_keys, joined_one_a);
  count :bat[:lng] := aggr.subcount(grouped_one_a, grouped_one_a, group_keys, false);
  #                  values to aggregate ⬏               ⬑ group IDs            ⬑ skip nils? [no: COUNT(*)]
  io.print(keys_a, count);

  # ❺ Sort                                   desc↴      ↲stable
  (sorted_a, oidx, gidx) := algebra.sort(keys_a, true, false);
  result_a    :bat[:int] := algebra.projection(oidx, keys_a);
  result_count:bat[:lng] := algebra.projection(oidx, count);
  io.print(result_a, result_count);
```

Data Dependencies in MAL Program for Q_{12}

```
one     :bat[:oid] := sql.tid(sql, "sys", "one");
one_a0 :bat[:int] := sql.bind(sql, "sys", "one", "a", 0:int);             ❶ Scan one.a
one_a  :bat[:int] := algebra.projection(one, one_a0);

                                                                           ❶ // ❷
many   :bat[:oid] := sql.tid(sql, "sys", "many");
many_a0:bat[:int] := sql.bind(sql, "sys", "many", "a", 0:int);            ❷ Scan many.a
many_a :bat[:int] := algebra.projection(many, many_a0);

(left, right) := algebra.join(one_a, many_a, nil:bat, nil:bat, false, nil:lng);   ❸ Equi-Join
joined_one_a:bat[:int] := algebra.projection(left, one_a);

(grouped_one_a, group_keys, group_sizes) := group.groupdone(joined_one_a);
keys_a:bat[:int] := algebra.projection(group_keys, joined_one_a);               ❹ Group + Agg
count :bat[:lng] := aggr.subcount(grouped_one_a, grouped_one_a, group_keys, false);

(sorted_a, oidx, gidx) := algebra.sort(keys_a, true, false);
result_a    :bat[:int] := algebra.projection(oidx, keys_a);                 ❺ Sort
result_count:bat[:lng] := algebra.projection(oidx, count);
```

Consider Q_{13}, returning the single value 42:

```
SELECT 42 AS fortytwo
FROM   hundred AS h₁, …, hundred AS hₙ  -- ⚠ 100ⁿ rows
LIMIT  1
```



Demonstrate the materialized/demand-driven evaluation of query evaluation plans.

- Shell: use

  `$ top -r -stats pid,command,cpu,vsize,pageins -pid (pgrep -f mserver5)`

  to observe memory allocation and paging behavior of MonetDB's server process.

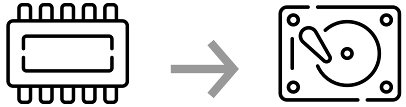
```
-- ❶ MonetDB: prepare input table

  DROP TABLE IF EXISTS hundred;

  CREATE TABLE hundred (i int);
  INSERT INTO hundred(i)
    SELECT value
    FROM   generate_series(1, 101); -- 100 rows

  \d hundred

-- Evaluate large cross-products (⚠ materialization)

  SELECT 42 AS fortytwo
  FROM   hundred AS h1, hundred AS h2, hundred AS h3
  LIMIT 1;
+----------+
| fortytwo |
+==========+
|       42 |
+----------+
1 tuple (17.635ms)


  SELECT 42 AS fortytwo
  FROM   hundred AS h1, hundred AS h2, hundred AS h3, hundred AS h4
  LIMIT 1;
+----------+
| fortytwo |
+==========+
|       42 |
+----------+
1 tuple (1.8s) ≈ 100 × 17.635 ms ✓


  EXPLAIN
    SELECT 42 AS fortytwo
    FROM   hundred AS h1, hundred AS h2, hundred AS h3, hundred AS h4
```

```
    LIMIT 1;
[...]
  X_5 := sql.mvc();
  C_8:bat[:oid] := sql.tid(X_5, "sys", "hundred");
  X_11:bat[:int] := sql.bind(X_5, "sys", "hundred", "i", 0:int);
  X_20 := algebra.projection(C_8, X_11);
  (X_28, X_29) := algebra.crossproduct(X_20, X_20);    ⚠ materialized cross product
  X_30 := algebra.projection(X_28, X_20);
  (X_39, X_40) := algebra.crossproduct(X_30, X_20);    ⚠ materialized cross product
  X_41 := algebra.projection(X_39, X_30);
  (X_52, X_53) := algebra.crossproduct(X_41, X_20);    ⚠ materialized cross product
  X_54 := algebra.projection(X_52, X_41);
  X_59 := algebra.project(X_54, 42:bte);
  C_67 := algebra.subslice(X_59, 0:lng, 0:lng);
  X_68 := algebra.projection(C_67, X_59);
[...]



  -- ⚠️ Does NOT terminate in reasonable time, need to kill mclient and mserver5
  --      (huge virtual memory size [VSIZE], all PhysMem used, heavy swapping, < 30% CPU utlization)
  SELECT 42 AS fortytwo
  FROM   hundred AS h1, hundred AS h2, hundred AS h3, hundred AS h4, hundred AS h5
  LIMIT 1;




-- ❷ PostgreSQL: prepare input table

  DROP TABLE IF EXISTS hundred;

  CREATE TABLE hundred (i int);
  INSERT INTO hundred(i)
    SELECT i
    FROM   generate_series(1, 100) AS i;

  \d hundred


-- Evaluate large cross-products (demand-driven pipelining)

  SELECT 42 AS fortytwo
  FROM   hundred AS h1, hundred AS h2, hundred AS h3
  LIMIT 1;

 ┌──────────┐
 │ fortytwo │
```

```
┌──────────┐
│       42 │
└──────────┘
Time: 0.925 ms

  SELECT 42 AS fortytwo
  FROM   hundred AS h1, hundred AS h2, hundred AS h3, hundred AS h4
  LIMIT 1;

┌──────────┐
│ fortytwo │
├──────────┤
│       42 │
└──────────┘
Time: 0.543 ms

  SELECT 42 AS fortytwo
  FROM   hundred AS h1, hundred AS h2, hundred AS h3, hundred AS h4, hundred AS h5
  LIMIT 1;

┌──────────┐
│ fortytwo │
├──────────┤
│       42 │
└──────────┘
Time: 0.667 ms


  EXPLAIN (ANALYZE, BUFFERS, COSTS FALSE)
    SELECT 42 AS fortytwo
    FROM   hundred AS h1, hundred AS h2, hundred AS h3, hundred AS h4, hundred AS h5
    LIMIT 1;

┌──────────────────────────────────────────────────────────────────────────────────────────────────────┐
│                                              QUERY PLAN                                              │
├──────────────────────────────────────────────────────────────────────────────────────────────────────┤
│ Limit (actual time=0.099..0.099 rows=1 loops=1)                                                      │
│   Buffers: shared hit=5 ← essentially only constant buffer space needed                              │
│   ->  Nested Loop (actual time=0.097..0.097 rows=1 loops=1)                                          │
│         Buffers: shared hit=5                                                                        │
│         ->  Nested Loop (actual time=0.083..0.083 rows=1 loops=1)                                    │
│               Buffers: shared hit=4                                                                  │
│               ->  Nested Loop (actual time=0.065..0.065 rows=1 loops=1)                              │
│                     Buffers: shared hit=3                                                            │
│                     ->  Nested Loop (actual time=0.046..0.046 rows=1 loops=1)                        │
│                           Buffers: shared hit=2                                                      │
│                           ->  Seq Scan on hundred h1 (actual time=0.022..0.022 rows=1 loops=1)       │
│                                 Buffers: shared hit=1                                                │
│                           ->  Materialize (actual time=0.021..0.021 rows=1 loops=1)                  │
│                                 Buffers: shared hit=1                                                │
```

```
                                  ->  Seq Scan on hundred h2 (actual time=0.010..0.010 rows=1 loops=1)
                                        Buffers: shared hit=1
                      ->  Materialize (actual time=0.018..0.018 rows=1 loops=1)
                            Buffers: shared hit=1
                            ->  Seq Scan on hundred h3 (actual time=0.010..0.010 rows=1 loops=1)
                                  Buffers: shared hit=1
                ->  Materialize (actual time=0.018..0.018 rows=1 loops=1)
                      Buffers: shared hit=1
                      ->  Seq Scan on hundred h4 (actual time=0.010..0.010 rows=1 loops=1)
                            Buffers: shared hit=1
          ->  Materialize (actual time=0.012..0.012 rows=1 loops=1)
                Buffers: shared hit=1
                ->  Seq Scan on hundred h5 (actual time=0.009..0.009 rows=1 loops=1)
                      Buffers: shared hit=1
Planning time: 0.472 ms
Execution time: 0.191 ms
```

Volcano-Style Demand-Driven Pipelining



PostgreSQL implements the **Volcano Iterator Model:**

- Operator **demands** its subplan to produce the next row (*i.e.*, the plan root drives the query evaluation).
- Operator delivers results **one row at a time**, avoids intermediate result materialization (if possible ⚠️):
  - Reduces query *response* time (first row delivered immediately, do not wait until result is complete). 👍
  - Reduces memory requirements (pass data row-by-row, not table at a time). 👍

Demand-Driven Evaluation and Call by Need

Volcano-style **demand-driven** pipelining bears some resemblance with **call-by-need** evaluation of (functional) programming languages:

- If function $f(e_1,e_2)$ does not (always) need the value of expression e_2, then $f(42,1/0)$ may evaluate just fine.
- With the demand-driven evaluation in Haskell[2], consider:

```
sum [ x/0 | x <- [1..10], x > 42 ]  ⇢  0.0

length [ x/0 | x <- [1..10] ]       ⇢  10
```

[2] Haskell is a *lazily* evaluated functional programming language, see http://haskell.org.

Demonstrate demand-driven evaluation and the NON-evaluation of parts of a query plan.

```
-- ❶ Check input tables

  \d one
                Table "public.one"
```

Column	Type	Collation	Nullable	Default
a b c	integer text integer		not null	

```
Indexes:
    "one_a" PRIMARY KEY, btree (a)
Referenced by:
    TABLE "many" CONSTRAINT "many_a_fkey" FOREIGN KEY (a) REFERENCES one(a)


  \d many
                Table "public.many"
```

Column	Type	Collation	Nullable	Default
a b c	integer text integer		not null not null	

```
Indexes:
    "many_a_c" PRIMARY KEY, btree (a, c)
Foreign-key constraints:
    "many_a_fkey" FOREIGN KEY (a) REFERENCES one(a)


-- ❷ Join query in which one leg yields the empty table ⇛ other leg
     not evaluated at all

  set enable_hashjoin = off;

  EXPLAIN (VERBOSE, ANALYZE)
    SELECT o.a / 0
    FROM   one AS o, many AS m
    WHERE  o.c = m.c
      AND  m.b = 'Ben Kenobi';  -- ← never satisfied ⇛ input leg 'many' yields no rows
```

```
                                   QUERY PLAN
Merge Join  (cost=10869.80..10972.01 rows=5216 width=4) (actual time=107.661..107.661 rows=0 loops=1)
  Output: (o.a / 0)
  Merge Cond: (m.c = o.c)
  ->  Sort  (cost=10031.41..10031.55 rows=56 width=4) (actual time=107.660..107.660 rows=0 loops=1)
        Output: m.c
        Sort Key: m.c
        Sort Method: quicksort  Memory: 25kB
        ->  Seq Scan on public.many m  (cost=0.00..10029.79 rows=56 width=4) (actual time=107.652..107.652 rows=0 loops=1)
              Output: m.c
              Filter: (m.b = 'Ben Kenobi'::text)
              Rows Removed by Filter: 505183
  ->  Sort  (cost=838.39..863.39 rows=10000 width=8) (never executed)
        Output: o.a, o.c
        Sort Key: o.c
        ->  Seq Scan on public.one o  (cost=0.00..174.00 rows=10000 width=8) (never executed)
              Output: o.a, o.c
Planning time: 0.175 ms
Execution time: 107.702 ms
```

Query Response vs. Evaluation Time

In PostgreSQL's EXPLAIN output, query **response** (first row) and **evaluation time** (all rows) are distinguished:

```
  ⋮
 Seq Scan on many m (actual time=0.747..139.172 rows=502867 …)
```

$\underbrace{\texttt{0.747}}\texttt{..}\underbrace{\texttt{139.172}}$ **response**/**evaluation** time

- Both times may…
  - … differ substantially (pipelined evaluation),
  - … coincide (**blocking** operators—*e.g.*, Sort—evaluate in full first, then deliver all rows from intermediate result buffer).

Demonstrate how response and evaluation may differ/coincide for different (non-)blocking operator kinds.

```
-- ❶ Check input table

  \d many
                 Table "public.many"
 Column │  Type   │ Collation │ Nullable │ Default
────────┼─────────┼───────────┼──────────┼─────────
 a      │ integer │           │ not null │
 b      │ text    │           │          │
 c      │ integer │           │ not null │
Indexes:
    "many_a_c" PRIMARY KEY, btree (a, c)
Foreign-key constraints:
    "many_a_fkey" FOREIGN KEY (a) REFERENCES one(a)


-- ❷ Seq Scan w/ Filter (fully pipelined)

EXPLAIN (ANALYZE, COSTS false)
  SELECT m.b
  FROM   many AS m
  WHERE  m.a > 42;
                              QUERY PLAN
──────────────────────────────────────────────────────────────────────
 Seq Scan on many m (actual time=0.787..144.830 rows=502867 loops=1)
   Filter: (a > 42)
   Rows Removed by Filter: 2316
 Planning time: 0.135 ms
 Execution time: 174.194 ms



-- ❷ Sort Filter (blocking)

EXPLAIN (ANALYZE, COSTS false)
  SELECT m.b
  FROM   many AS m
  WHERE  m.a > 42
  ORDER BY m.b;
                              QUERY PLAN
──────────────────────────────────────────────────────────────────────────
```

```
 Sort (actual time=2609.184..3473.799 rows=502867 loops=1)
   Sort Key: b
   Sort Method: external merge  Disk: 13312kB
   ->  Seq Scan on many m (actual time=0.846..141.182 rows=502867 loops=1)
         Filter: (a > 42)
         Rows Removed by Filter: 2316
 Planning time: 0.178 ms
 Execution time: 3504.668 ms
```

```
-- ❸ Aggregate (blocking, result tiny)

EXPLAIN (ANALYZE, COSTS false)
  SELECT COUNT(m.b)
  FROM   many AS m
  WHERE  m.a > 42;
```

```
                         QUERY PLAN
--------------------------------------------------------------------------
 Aggregate (actual time=228.496..228.496 rows=1 loops=1)
   ->  Seq Scan on many m (actual time=0.498..125.060 rows=502867 loops=1)
         Filter: (a > 42)
         Rows Removed by Filter: 2316
 Planning time: 0.147 ms
 Execution time: 228.534 ms
```

```
-- ❸ Grouped Aggregate over sorted input (⚠️ first group(s) delivered BEFORE blocking Sort is done)
--   Q: How is this possible?
--   A: Grouping/aggregtation folded into Sort's final merge phase)
--
-- See PostgreSQL source (src/backend/utils/sort/tuplesort.c):
-- ``When the caller requests random access to the sort result, we form
--   the final sorted run on a logical tape which is then "frozen", so
--   that we can access it randomly.  When the caller does not need random
--   access, we return from tuplesort_performsort() as soon as we are down
--   to one run per logical tape.  The final merge is then performed
--   on-the-fly as the caller repeatedly calls tuplesort_getXXX;      ← this is our next()
--   this saves one cycle of writing all the data out to disk and
--   reading it in.''

 EXPLAIN (ANALYZE, COSTS false)
   SELECT m.c, COUNT(m.b)
   FROM   many AS m
   WHERE  m.a > 42
```

```
GROUP BY m.c;
```

```
                              QUERY PLAN
GroupAggregate (actual time=406.329..612.823 rows=101 loops=1)
  Group Key: c                                                          406.329 < 505.390
  ->  Sort (actual time=402.426..505.390 rows=502867 loops=1)
        Sort Key: c
        Sort Method: external merge  Disk: 15288kB
        ->  Seq Scan on many m (actual time=0.754..145.046 rows=502867 loops=1)
              Filter: (a > 42)
              Rows Removed by Filter: 2316
Planning time: 0.233 ms
Execution time: 617.946 ms
```

Volcano Iterator Model: API

In Volcano-style demand-driven query evaluation, operators implement a simple API of three main methods:

1. **open()**: Initialize operator and its internal state, forward open() request to upstream subplans as well.
2. **next()**: If required, forward next() upstream to request more input rows. Then deliver next output row (or NULL if result complete).
3. **close()**: Release operator-internal state, forward close() request to upstream subplans as well.

Volcano-style call protocol: (open() next()* close())$^+$.

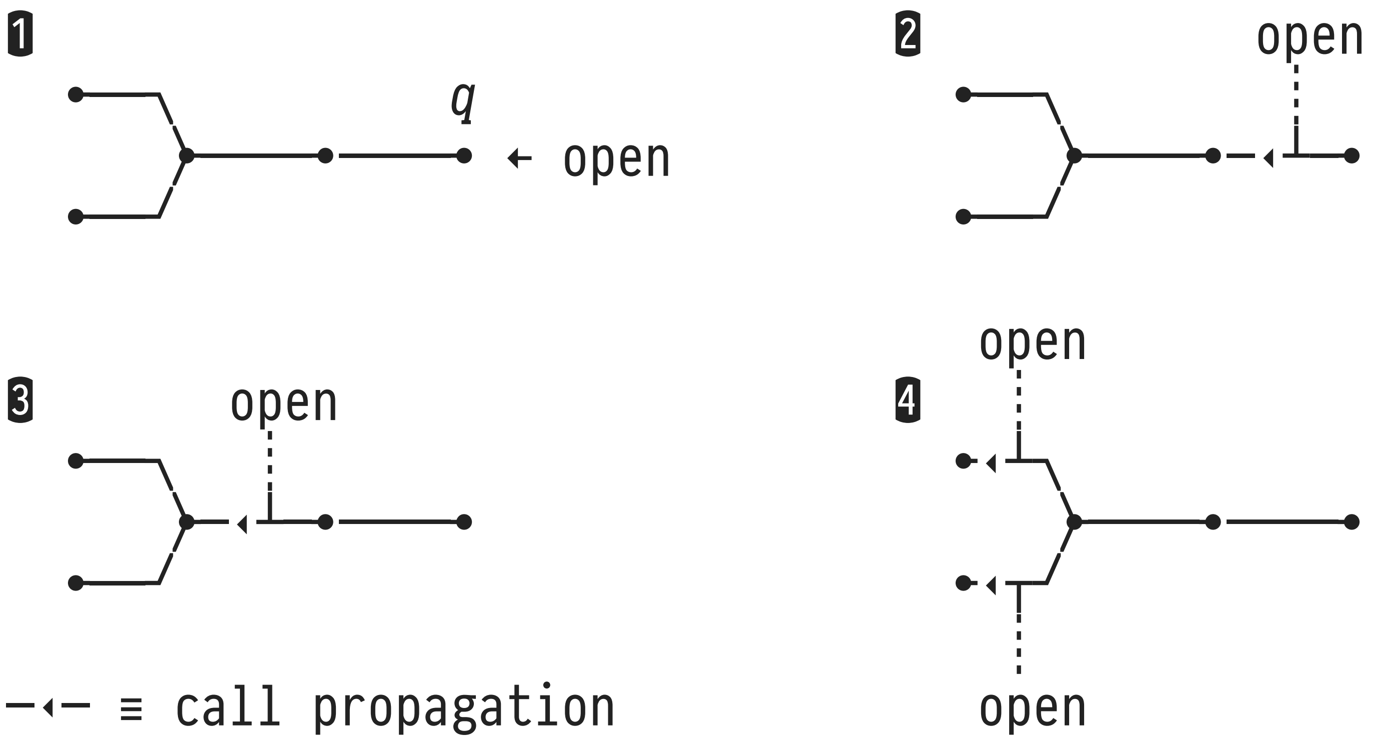
Volcano Iterator Model: Query Evaluation Driver

Use the Volcano iterator model API to *fully* evaluate a query. Operator q denotes the root of the query plan:

```
Eval(q):
  open(q);
  t ← next(q);
  while t ≠ NULL                 } iterate while still rows to consume
   | emit(t);                    } ship current row to application
   | t ← next(q);
  close(q);
```

- To retrieve next result row only, simply call next(q).
- May/must use close(q) to cancel query evaluation midway.

Volcano Iterator Model: Forwarding open()/close()



- Each operator instance (•) allocates and releases its own copy of state that is kept between method invocations.

Pipelined Nested Loop Join (NLJ) ❶

Implement open() and close() for the Nested Loop Join operator:

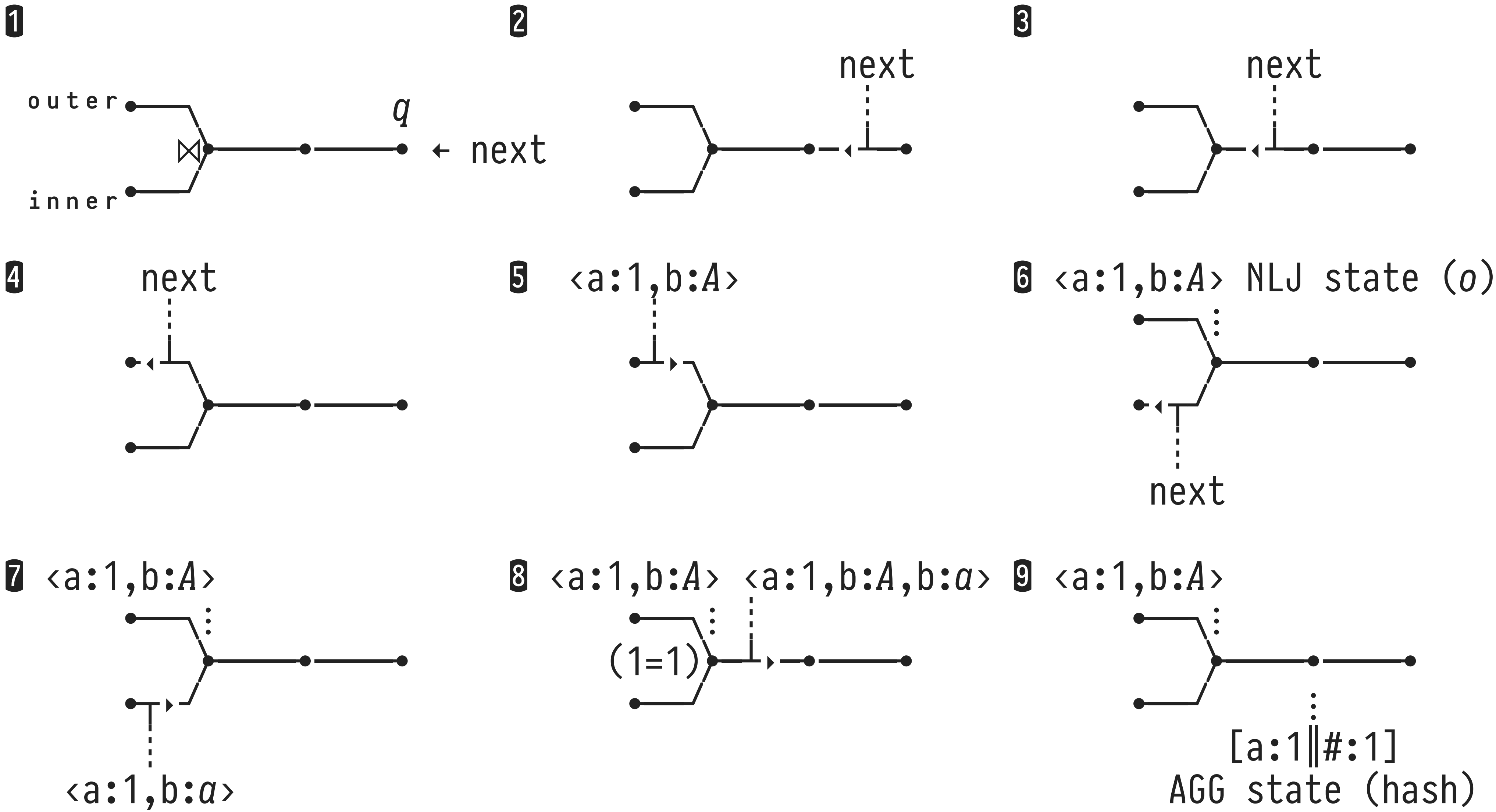
```
NLJ.open(outer,inner,θ):
  open(outer);                ⎫ may open() in ∥:
  open(inner);                ⎭             outer inner

  needNewOuter ← true;        ⎫ local NLJ state
  o            ← NUL;         ⎭
```

```
NLJ.close(outer,inner,θ):
  close(outer);
  close(inner);
```

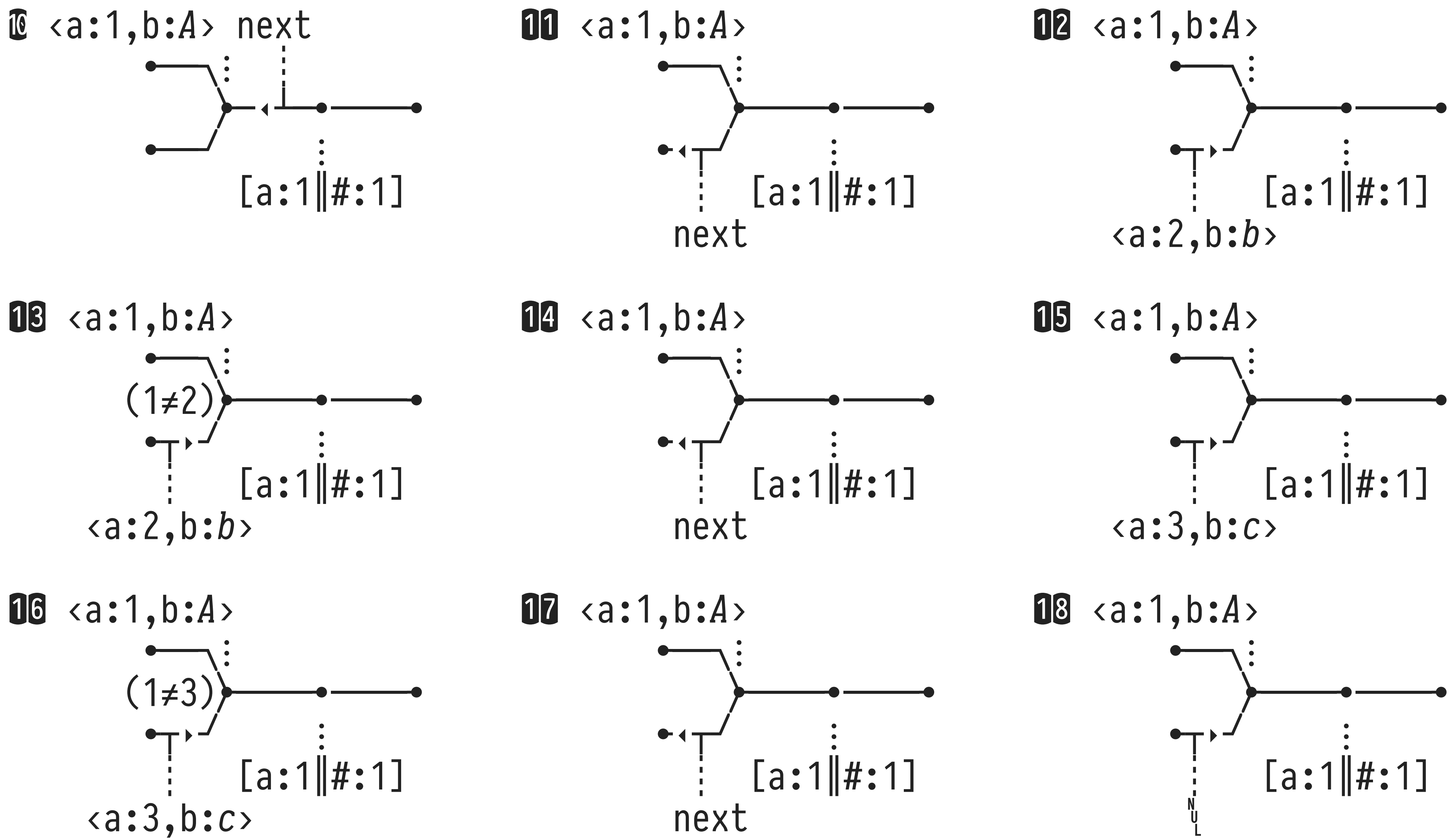
Pipelined Nested Loop Join (NLJ) ❷

```
NLJ.next(outer,inner,θ):
  forever
    if needNewOuter
      o ← next(outer);             } o: current outer row
      if o = NULL                  ⎱ no more outer rows
        return NULL;               ⎰  ⇒ join complete
      needNewOuter ← false;
      close(inner);                ⎱ reset/rescan
      open(inner);                 ⎰  inner input

    i ← next(inner);               } i: current inner row
    if i = NULL                    ⎱ no more inner rows,
      needNewOuter ← true;         ⎰  next time: read new outer
    else if o θ i                  } join condition satisfied?
           return ⟨o,i⟩;           } return single joined pair
```

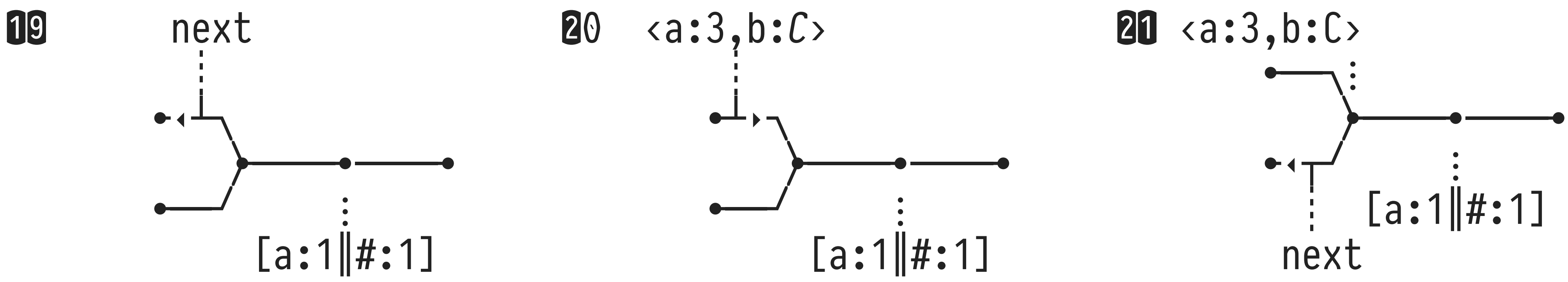
Volcano Iterator Model: Evaluating a NLJ Plan



Volcano Iterator Model: Evaluating a NLJ Plan



Volcano Iterator Model: Evaluating a NLJ Plan



Quiz/Exercise: Think about how to implement the following plan operators in the Volcano iterator model:

- Seq Scan (with Filter condition),
- Limit (given a row limit *n*),
- GroupAggregate (over input sorted by the Group Key),
- Append (SQL: UNION ALL).

Volcano Iterator Model at the SQL Level

Via **cursors**, the SQL standard exposes the Volcano-style open/next/close API at the level of (Embedded) SQL:

```
-- Generate query plan, no evaluation yet
❶ DECLARE ‹cursor› [ SCROLL ] CURSOR FOR ‹query›
--                     ⬑ cursor can move backwards

-- Evaluate plan to deliver the next/prior row (‹n› rows)
❷ FETCH [ NEXT | [ FORWARD | BACKWARD ] ‹n› ] FROM ‹cursor›

-- Release plan/intermediate buffers
❸ CLOSE ‹cursor›
```

- Statements need to be issued within an SQL transaction.

Demonstrate the SQL-level Volcano-style cursor interface.

```
-- 1 Check input tables
  \d one
```

Table "public.one"

Column	Type	Collation	Nullable	Default
a	integer		not null	
b	text			
c	integer			

```
Indexes:
    "one_a" PRIMARY KEY, btree (a)
Referenced by:
    TABLE "many" CONSTRAINT "many_a_fkey" FOREIGN KEY (a) REFERENCES one(a)


  \d many
```

Table "public.many"

Column	Type	Collation	Nullable	Default
a	integer		not null	
b	text			
c	integer		not null	

```
Indexes:
    "many_a_c" PRIMARY KEY, btree (a, c)
Foreign-key constraints:
    "many_a_fkey" FOREIGN KEY (a) REFERENCES one(a)


-- 2 Declare/fetch/close cursor for join query (within a SQL transaction)

  BEGIN;

  DECLARE pipeline SCROLL CURSOR FOR
    SELECT DISTINCT o.a, o.b || m.b AS md5
    FROM   one AS o, many AS m
    WHERE o.a = m.a;

  FETCH NEXT pipeline;
```

a	md5

```
| 1 | c4ca4238a0b923820dcc509a6f75849b |
Time: 896.523 ms  -- ← ⚠️ first fetch takes time (evaluate the blocking DISTINCT)

  FETCH NEXT pipeline;
```

a	md5
2	c81e728d9d4c2f636f067f89cc14862c

```
Time: 0.177 ms  -- ← ⚠️ subsequent fetches are immediate

  FETCH FORWARD 3 pipeline;
```

a	md5
3	eccbc87e4b5ce2fe28308fd9f2a7baf3
4	a87ff679a2f3e71d9181a67b7542122c
5	e4da3b7fbbce2345d7772b0674a318d5

```
Time: 0.252 ms

  FETCH BACKWARD 2 pipeline;
```

a	md5
4	a87ff679a2f3e71d9181a67b7542122c
3	eccbc87e4b5ce2fe28308fd9f2a7baf3

```
Time: 0.231 ms

  CLOSE pipeline;

  COMMIT;
```

⚠️ **Nice:** Illustrate the implementation of plan operator Append (SQL: UNION ALL). **Q:** Let students speculate about the behavior:

```
-- Query will generate six rows (i = 1…6)
EXPLAIN
  SELECT i FROM generate_series(1,3) AS i
    UNION ALL
  (SELECT i
   FROM   generate_series(10000000,4,-1) AS i
   ORDER BY i
   LIMIT 3);
```

```
                                         QUERY PLAN
Append  (cost=0.00..32.97 rows=1003 width=4)
  ->  Function Scan on generate_series i  (cost=0.00..10.00 rows=1000 width=4)
  ->  Limit  (cost=22.93..22.93 rows=3 width=4)
        ->  Sort  (cost=22.93..25.43 rows=1000 width=4)
              Sort Key: i_1.i
              ->  Function Scan on generate_series i_1  (cost=0.00..10.00 rows=1000 width=4)
```

```
BEGIN;

DECLARE pipeline CURSOR FOR
  SELECT i FROM generate_series(1,3) AS i
    UNION ALL
  (SELECT i
   FROM   generate_series(10000000,4,-1) AS i
   ORDER BY i
   LIMIT 3);

FETCH NEXT pipeline;  -- takes    22 ms [first row from left leg of UNION ALL]
FETCH NEXT pipeline;  --         0.2 ms [subequent rows from left leg]
FETCH NEXT pipeline;  --         0.2 ms
FETCH NEXT pipeline;  --       5000+ ms [first row from right leg, evaluates costly blocking Sort]
FETCH NEXT pipeline;  --         0.2 ms [subequent rows from right leg]
FETCH NEXT pipeline;  --         0.2 ms

CLOSE pipeline;

COMMIT;
```

Volcano-Style Iteration has its Cost

- Effectively, **multiple operators are active at one time.**
    - Aggregate intermediate state (memory) may be large.
    - Method call forwarding incurs function call overhead.
    - Frequent switches between code blocks due to row-by-row processing, CPU instruction cache misses are likely.

- 💡 Few modern RDBMSs (*X100* aka *VectorWise*[3]) seek middle ground between full materialization and pipelining:
    - Build demand-driven pipeline between operators, but…
    - … pass **vectors of rows**—typically the size of the CPU's data cache—between operators.

[3] See *MonetDB/X100—A DBMS In The CPU Cache* and *MonetDB/X100: Hyper-Pipelining Query Execution*.