Design and Implementation of DuckDB Internals

Query Execution Plans and Pipelining

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1 ¦ Query Execution ≡ Plan Execution

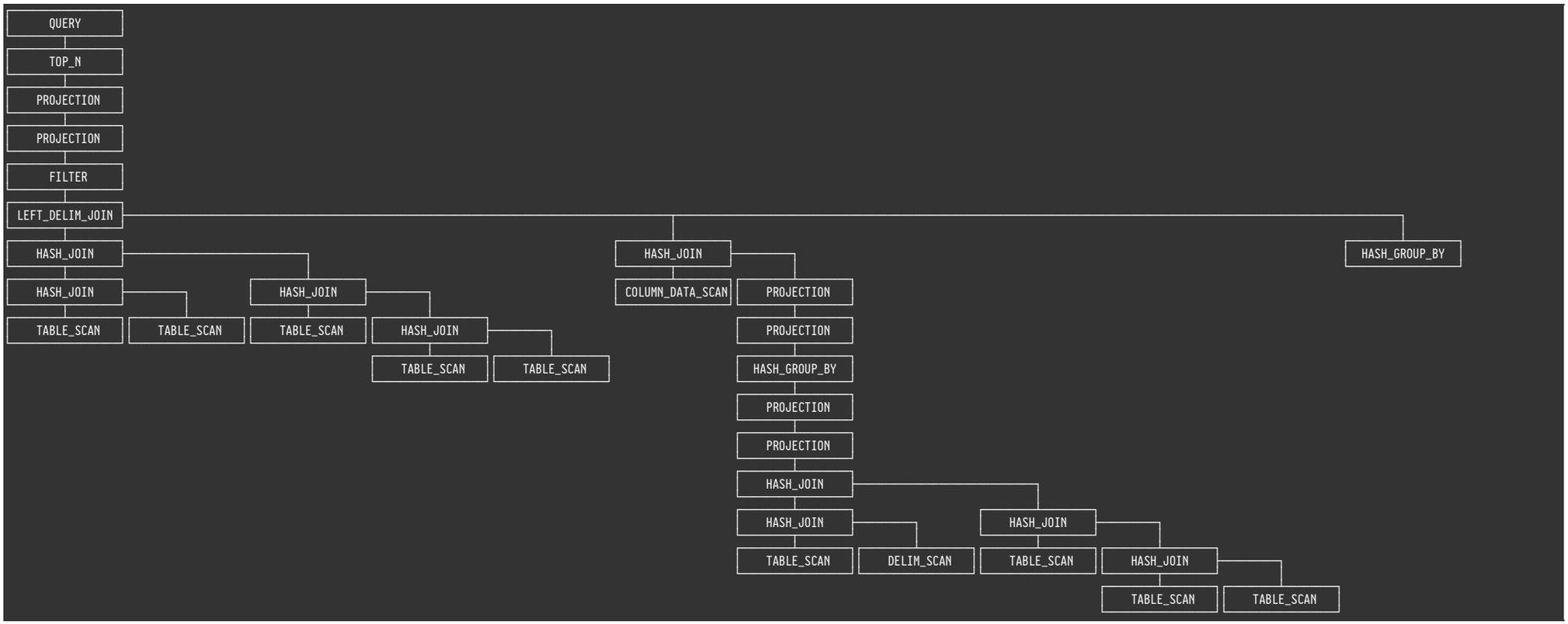
DuckDB translates SQL text into an **execution plan,** a tree-shaped[1] 🖧 data flow network:

- Nodes ▭ in this network are (physical) **operators,** each of which implement one computation step. Example operators:
  - TABLE_SCAN: reads rows from a table (leaf/source operator),
  - PROJECTION, FILTER: eval (Boolean) expressions, discard rows,
  - HASH_GROUP_BY: hash-based grouped aggregation.
- Edges are directed upwards/leftwards (▭┐ ≡ ▭◂┐) and route rows from child operator(s) to parent operator.
  - DuckDB: **data chunks** of 2048 rows flow jointly along.
- Rows returned by the root operator represent the query result.

[1] This is mostly true. Particular SQL features—e.g., correlated subqueries or common table expressions (CTEs)—can lead to DAG-shaped execution plans.

Execution Plans can be Complex

The execution plans of complex queries are intricate (TPC-H Q2):



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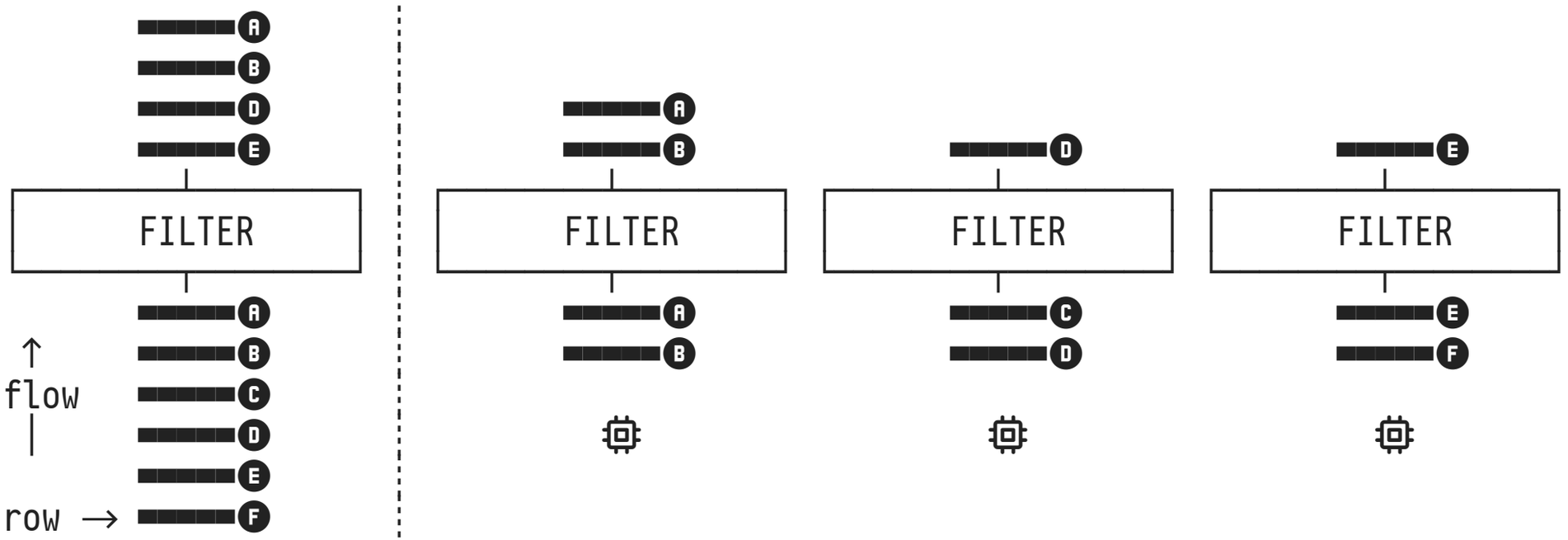
- **Q:** How to **orchestrate the data flow** such that DuckDB
  - does *not need to materialize intermediate results* and
  - and that all *CPU cores* *can equally contribute in parallel*?

2 ¦ Trivially Parallel Operators 1

Operators like FILTER (discard rows based on predicate) or PROJECTION (evaluate scalar expressions) are inherently parallel:

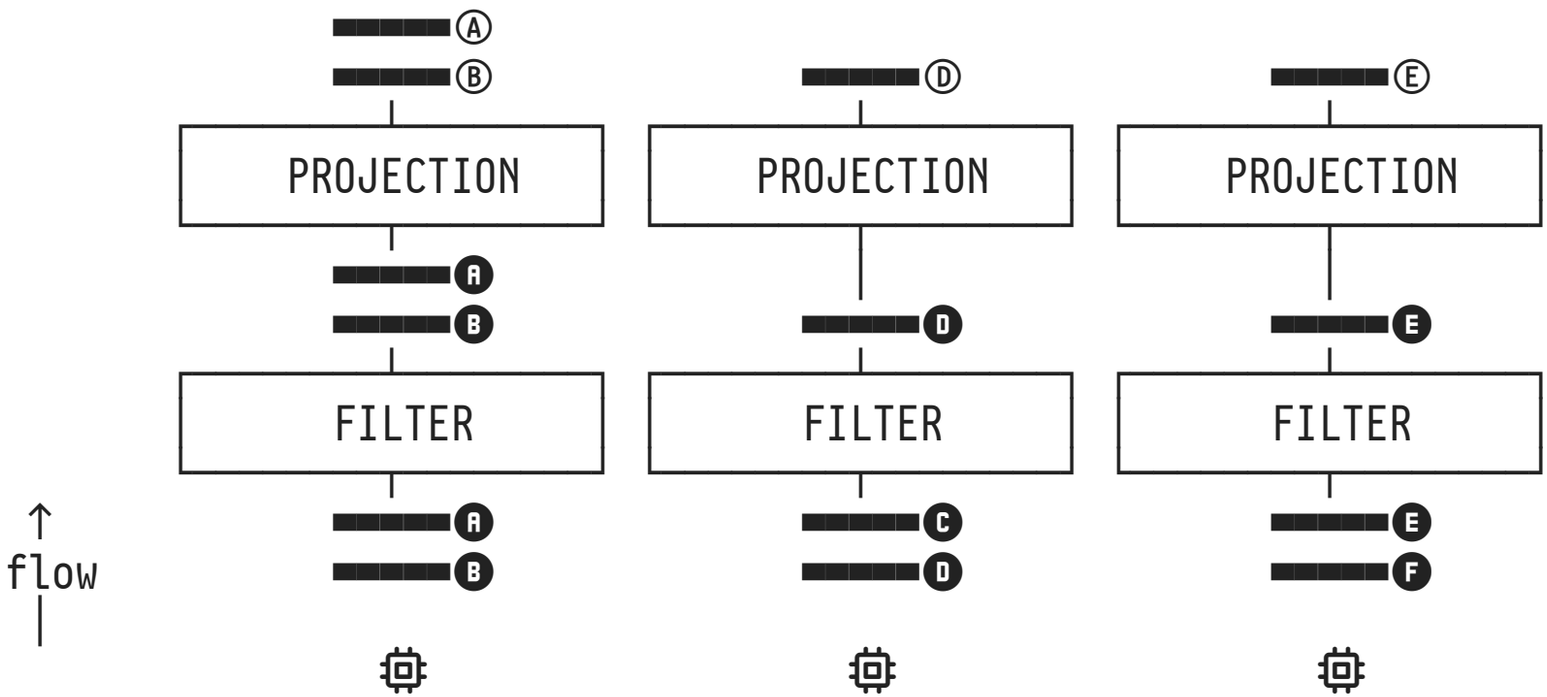
- Each thread operates on a partition of rows. Overall result is the (disjoint) union of all -local results.
- No inter-thread dependencies, operator implementation itself does need *not* to be aware of //ism.



Trivially Parallel Operators 2

Sequences of “PROJECTION-like” operators are assembled into **pipelines:**

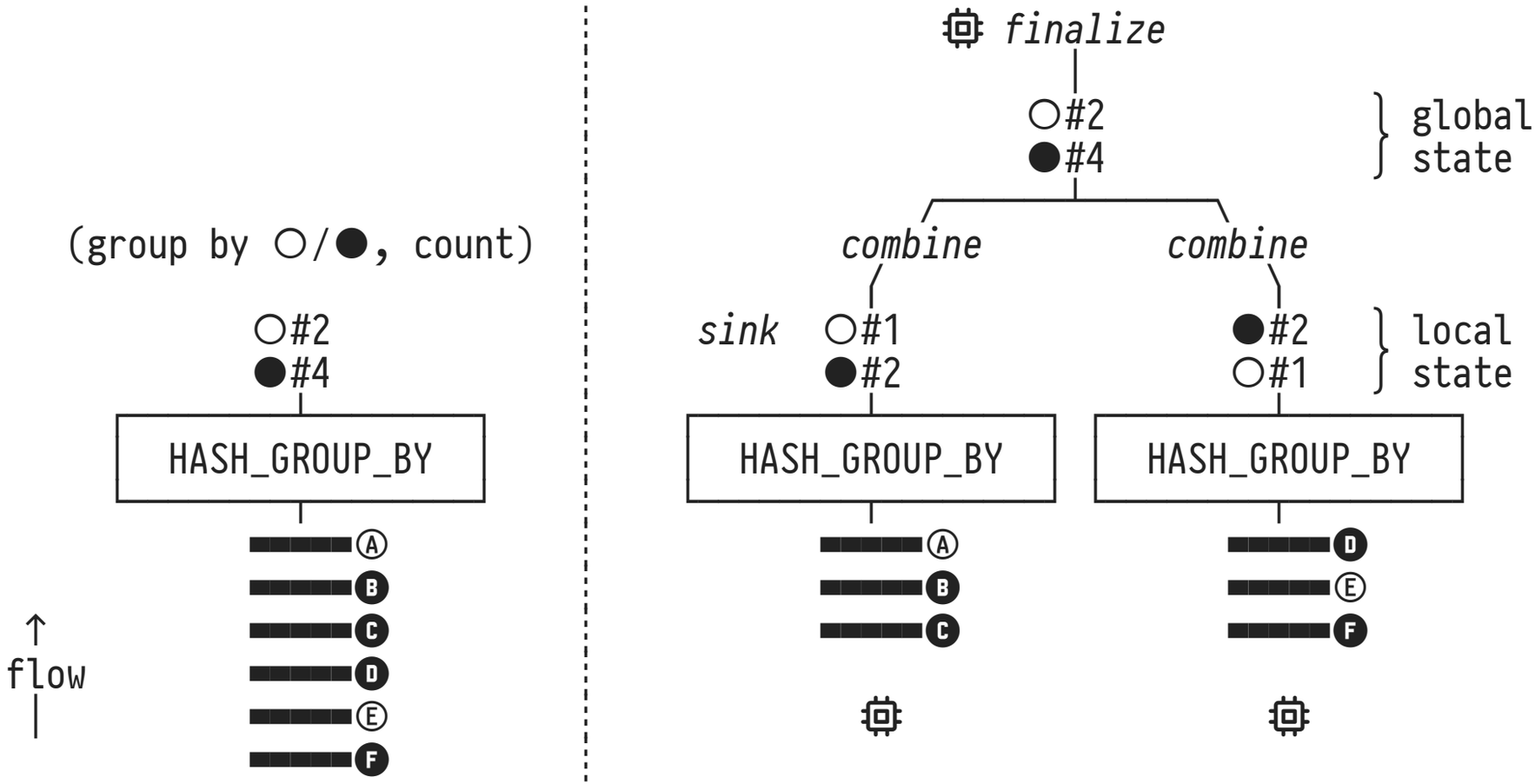
- Each thread/core runs its own instance of the pipeline.
- Data is passed between operators in **chunks** (2048 rows).[2]



[2] Rows that pass FILTER are buffered before they are pushed down the pipeline (do not pass “single-row chunks”—DuckDB aims to pass more than 64 rows). If *all* rows pass, simply pass on the input rows.

3 ¦ Pipeline-Breaking Operators 1

Operators like HASH_GROUP_BY produce a result only once the *entire row input* has been consumed:



Pipeline-Breaking Operators (Sinks) 2

"HASH_GROUP_BY-like" (DB lingo: **sinks**) operator phases:

1. ***Sink***: Each thread 🖳🖳 "sinks" all incoming data into its *local state* (e.g., HASH_GROUP_BY Phase ❶, recall Chapter 03).
2. ***Combine***: Once a thread has read its input, combine local state with the operator's *global state* (HASH_GROUP_BY, Phase ❷).
3. ***Finalize***: *Combine* done, a single thread 🖳 post-processes the global state which is then pushed to the next pipeline.

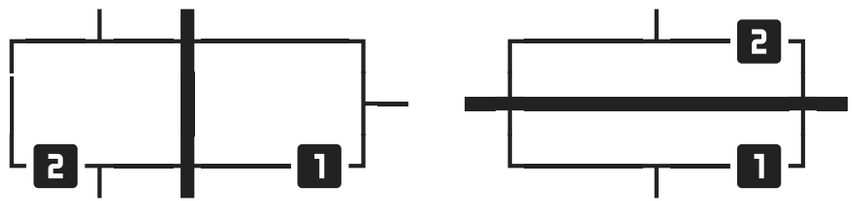
Sinks may only be placed at pipeline ends (**pipeline breakers**).

- Examples of sinks in DuckDB:
  - HASH_GROUP_BY (builds aggregate hash table)
  - Build side of HASH_JOIN (hash table for rhs join input)
  - ORDER_BY (local state: sorted run)
  - UNGROUPED_AGGREGATE (local state: partial aggregate)

4 ¦ Assembling Execution Plans from Pipelines

Execution plans for non-trivial SQL queries are assembled by **stitching multiple pipelines together.**

- In the plans below, operators ▭ are tagged by ❶,❷,… to assign them to a pipeline. Pipeline breakers are marked using ╋.
- Operators like those on the right act like a sink for pipeline ❶. Their output can then be read by the subsequent pipeline ❷.



- Such operators introduce **pipeline dependencies:** ❶ < ❷ (pipeline ❶ must finalize before ❷ can read its output).
- Root operator QUERY acts as a sink that
  - collects all incoming rows and
  - constructs the final query result (to be shipped to the caller or displayed by the CLI).

Assembling Execution Plans from Pipelines

Sample query Q_1 over TPC-H data of medium complexity:[3]

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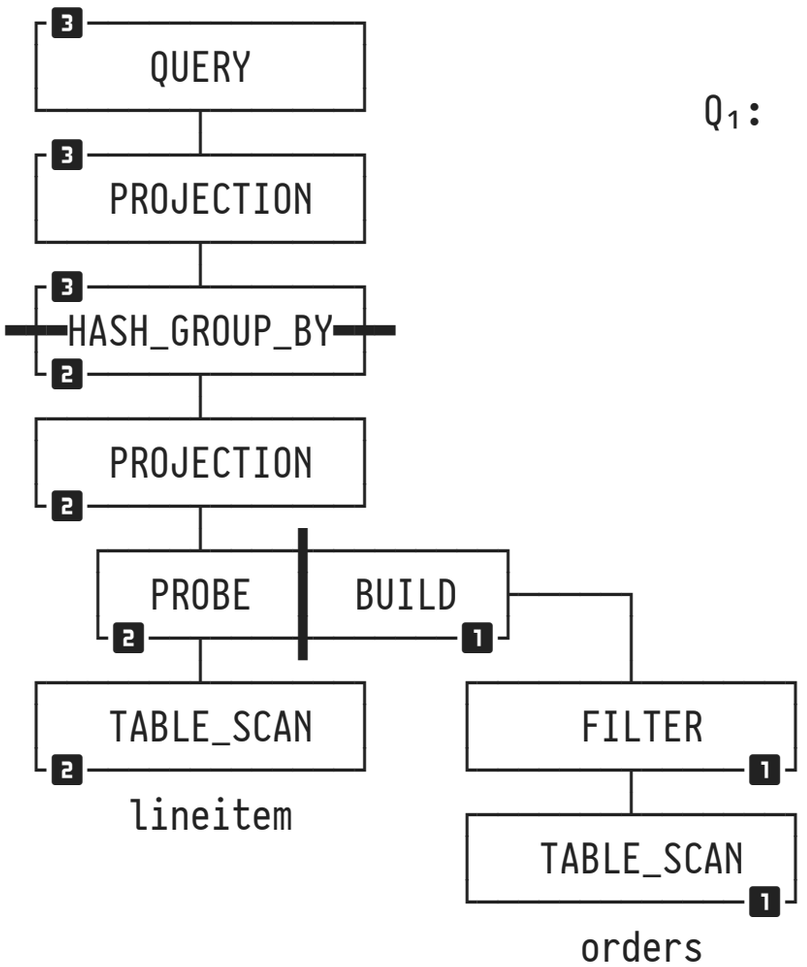


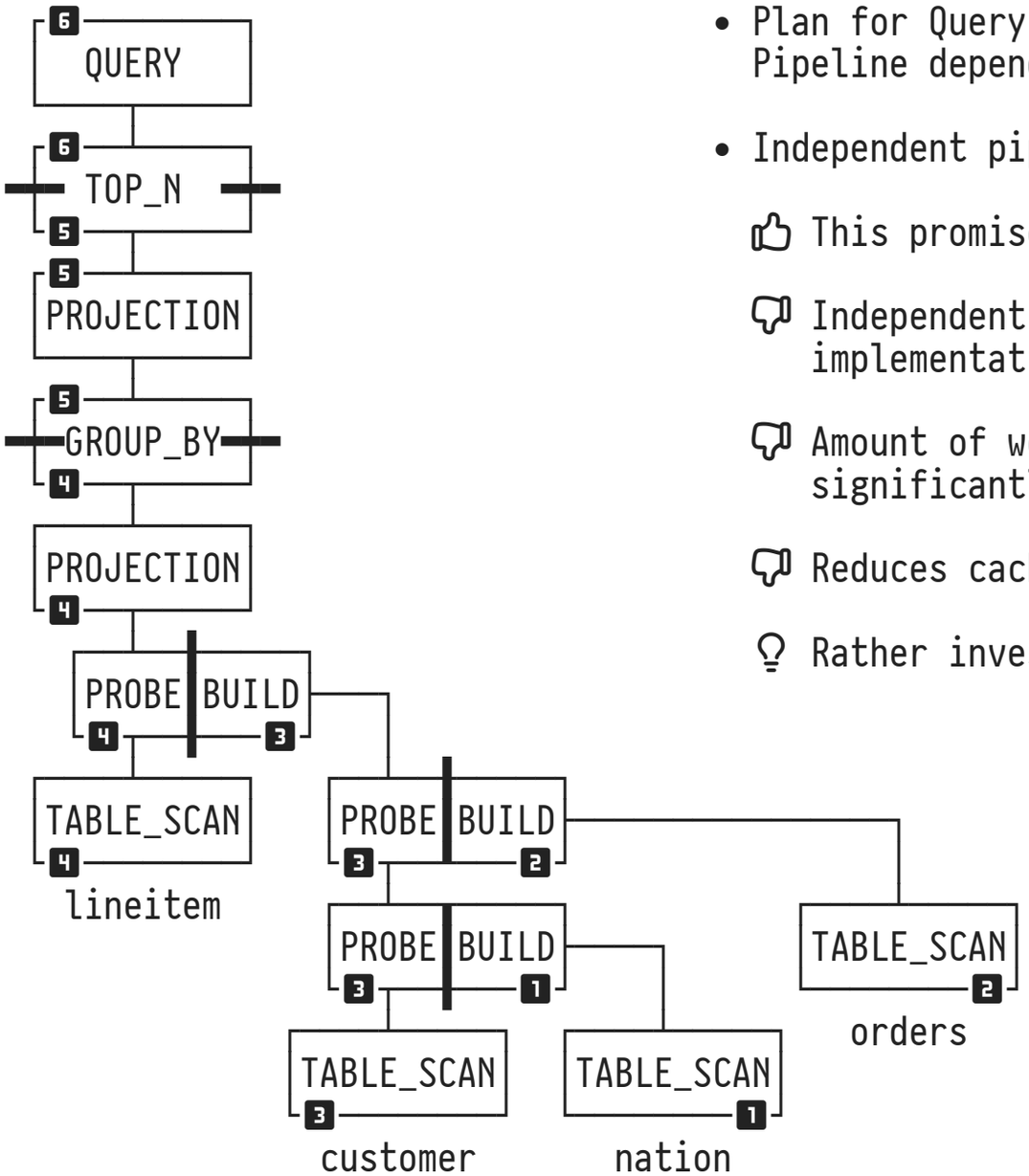
Q_1:

```
SELECT DISTINCT o.o_orderkey AS violation
FROM   lineitem AS l, orders AS o
WHERE  l.l_orderkey = o.o_orderkey
AND    o.o_orderstatus IN ('O', 'F')
AND    l.l_linestatus <> o.o_orderstatus;
```

- PROBE | BUILD ≡ HASH_JOIN
- For HASH_JOIN, DuckDB chooses the smaller input to be on the BUILD side.
- Pipeline dependencies: 1 < 2 < 3

[3] Checks for violations of a TPC-H constraint: o_orderstatus is set to 'O' ('F') iff all lineitems of this order have l_linestatus set to 'O' ('F'). See the TPC-H benchmark specification, §4.2.3.

Assembling Execution Plans from Pipelines

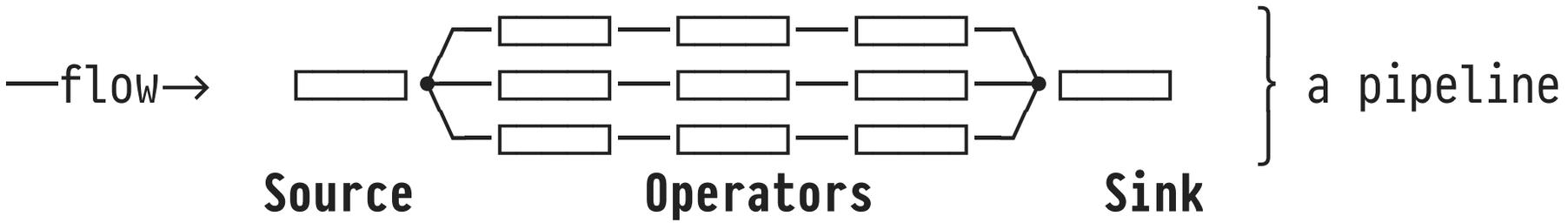


- Plan for Query Q_3 (TPC-H Query 10)
  Pipeline dependencies: (1 ‖ 2) < 3 < 4 < 5 < 6.
- Independent pipelines 1 ‖ 2 can be run in parallel:
  - 👍 This promises reduced latency.
  - 👎 Independent pipelines are rather rare. Does the implementation of the required logic pay off?
  - 👎 Amount of work in pipelines 1 and 2 may differ significantly.
  - 👎 Reduces cache locality.
  - 💡 Rather invest more cores in a single pipeline.

5 ¦ Parallelism in a Pipeline

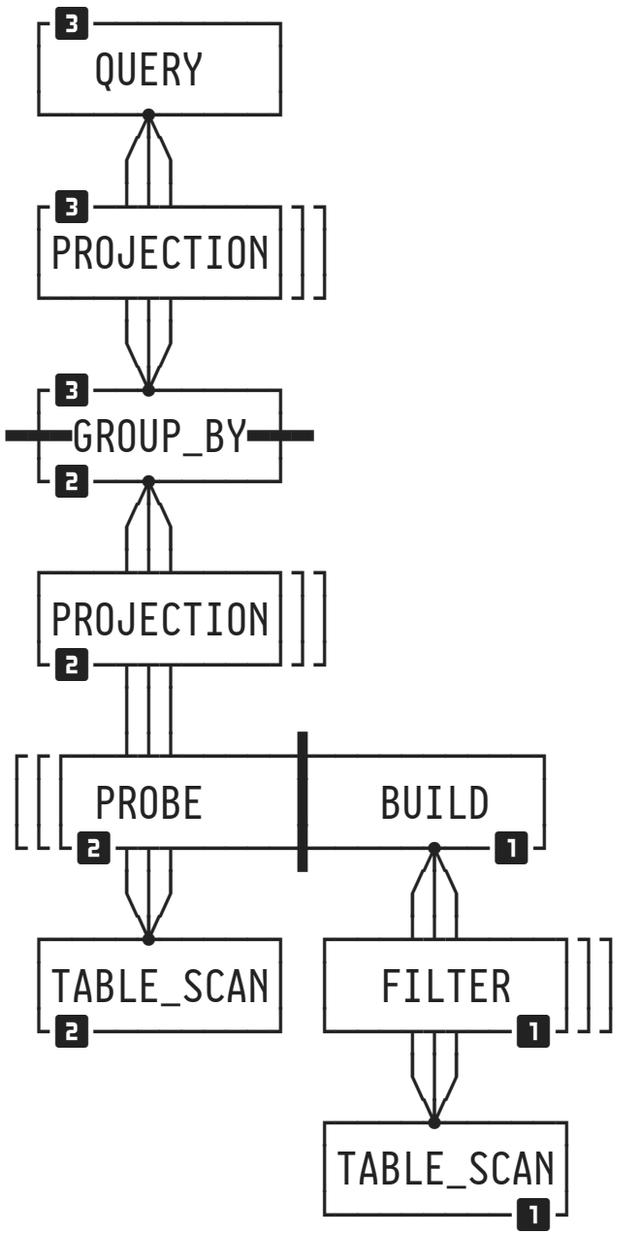
A pipeline in a DuckDB execution consists of three segments.

- **Sources** and **sinks** are parallelism-aware, **operators** need not be:



- Sources know how to partition rows. Examples:
  - COLUMN_DATA_SCAN (literal data), RANGE (row generator)
  - TABLE_SCAN (read base table), CTE_SCAN (read CTE)
  - READ_CSV, PARQUET_SCAN (read external file)
  - Some operators are sinks *and* sources: →⊏▌⊐←
    (HASH_GROUP_BY serves rows from its aggregate hash table).

Parallelism in a Pipeline



- Pipelines and parallelism in the plan for Q_1 (TPC-H constraint check, see above).
- Pipeline **sources** 🡐:
  1: TABLE_SCAN (orders)
  2: TABLE_SCAN (lineitem)
  3: Phase ❷ of HASH_GROUP_BY
- Pipeline **sinks** 🡒:
  1: BUILD phase of HASH_JOIN
  2: Phase ❶ of HASH_GROUP_BY
  3: QUERY root node
- PROBE side of HASH_JOIN is an operator: multiple threads can peek into the hash table in parallel.

6 ¦ Pipeline Execution

In DuckDB, **pipeline execution** is driven by a core loop (see next slide) that is run by each thread 🔲. This loop

- maintains operator state (🔲-local as well as global),
- receives data chunks from operators (or the source) and **pushes** these chunks towards the downstream operator (or the sink),
- contains control flow that detects whether
  1. the source is exhausted or
  2. an operator outputs an empty chunk.

The pipeline driver can

- *cache* rows in case a FILTER or PROBE returns few results (avoid the overhead of passing on tiny or single-row chunks),
- *split* the data flow and pass chunks to multiple consumers (e.g., to share the output of a TABLE_SCAN).

Sketch of DuckDB's Pipeline Driver (Run by each Thread)[4]

```
var operator[]   pipeline[0...P]          pipeline to execute (operator count P+1)
var state[]      states[0...P]            -local + global operator state
var data_chunk[] intermediates[0...P-1]   rows output by source/operators (intermediate results)

source ← pipeline[0]                      pipeline source and sink
sink   ← pipeline[P]                      (pipeline[1...P-1] are operators)

for i in 0...P:                           initial operator states
| states[i]        ← pipeline[i].GetOperatorState(...)
for i in 0...P-1:                         allocate intermediate chunks
| intermediates[i] ← data_chunk.Initialize(pipeline[i].return_type)

while true:
| intermediates[0] ← source.GetData(states[0], ...)  get next data chunk from 's morsel
| if (intermediates[0].size = 0)                     no more rows? 1
| | return FINISHED                                  └ yes, bail out
|
| reached_sink ← true
| for i in 1...P-1:                                  execute operators in pipeline order
| |  intermediates[i] ← pipeline[i].Execute(intermediates[i-1], states[i])
| |  if (intermediates[i].size = 0)                  operator reduced data chunk to size 0? 2
| |  | reached_sink ← false                          └ yes, restart at source with next chunk
| |  | break
|
| if reached_sink:                                   did non-empty data chunk reach the sink?
| | sink.Sink(intermediates[P-1], states[P], ...)    └ yes, collect rows at the sink
```

[4] The pseudo code for the pipeline driver is modelled after DuckDB GitHub issue 1583 .

Pipeline Driver Manages Control Flow, Operators are Simple

Since control flow is handled by the pipeline driver, source/operator/sink **implementations** turn out to be simple:

1. Build phase of HASH_JOIN (sink ❯):

```
HashJoinBuild.Sink(input, state):
| ht ← state.local_hash_table
└ ht.BuildHashTable(input)
```

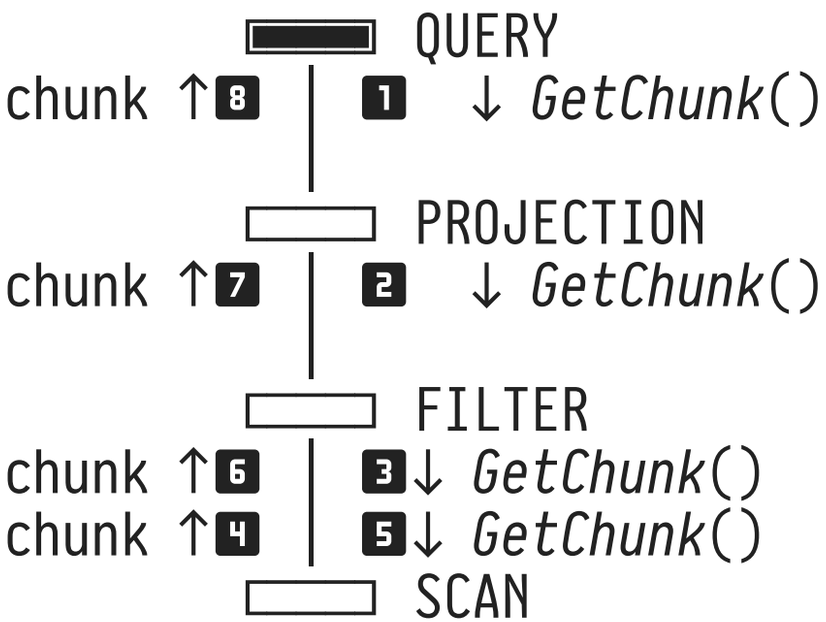
   The *Combine* phase of HASH_JOIN merges the 🔲-local hash tables into a global hash table that can be probed against.

2. Probe phase of HASH_JOIN (operator):

```
HashJoinProbe.Execute(input, state):
| ht ← state.global_hash_table
| joined ← ht.ProbeHashTable(input)
└ return joined
```

Not DuckDB: Pull-Based Execution (Volcano Iterator Model)

Prior to release 0.3.0 (October 2021), DuckDB implemented **pull-based** operators[5] without a pipeline driver:



1. Start at plan root ▬. Call *GetChunk*() on child operator to request next data chunk.
2. Operators forward *GetChunk*() call down the plan until leaves can return a chunk.
3. Operators process obtained chunk. Call *GetChunk*() again if all of chunk was filtered, otherwise pass chunk upwards.
4. Operators return FINISHED if no more chunks to deliver.

[5] This pull-based plan execution strategy is known as the Volcano iterator model. It is still widely implemented in today's DBMSs. Example: PostgreSQL 👎 (operators return a *single row* on each "GetChunk()" call).

Not DuckDB: Pull-Based Execution (Volcano Iterator Model)

Pseudo code for HASH_JOIN in the pull-based Volcano model:

- Control flow handled inside operator.
- Probe + build phases are entangled, hard to parallelize. 👎

```
HashJoin.GetChunk(probe, build):
  state ← this.GetOperatorState(...)
  ht ← state.hash_table

  if not state.build_done:                    are we in the build or probe phase?
    while true:                          ❶    build phase
      chunk ← build.GetChunk(...)             pull next chunk from build side
      if chunk.size = 0:                      no more rows?
        break                                 └ yes, hash table complete—now probe
      ht.BuildHashTable(chunk)                insert chunk into hash table
    state.build_done ← true

  do:                                    ❷    probe phase
    chunk ← probe.GetChunk(...)               pull next chunk from probe side
    if chunk.size = 0:                        no more rows?
      return FINISHED                         └ yes, join complete
    joined ← ht.ProbeHashTable(chunk)         probe chunk against hash table
  while joined.size = 0                       retry if no rows joined
  return joined
```