DuckDB

CWI

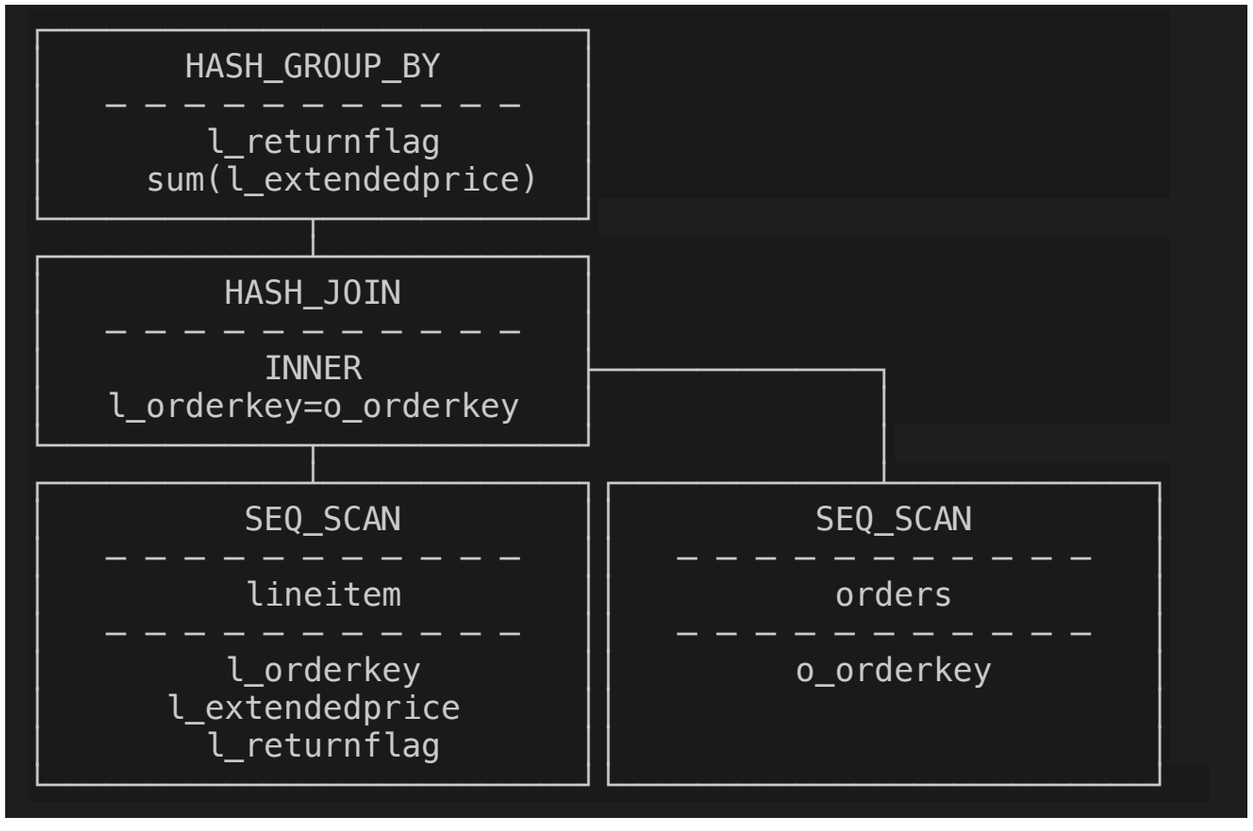
Push-Based Execution in DuckDB

Mark Raasveldt

Execution Recap

- DBMS transform SQL into query plans
- Query plans contain operators

```
SELECT SUM(l_extendedprice)
FROM lineitem
JOIN orders
ON (l_orderkey=o_orderkey)
GROUP BY l_returnflag;
```



- Operators need to be executed
- How?

- Two paradigms: Pull-based and push-based
- **Pull-based**
  - Pull data from other operators when required
- **Push-based**
  - Push data into operator when data is available

Pull-Based Execution

- DuckDB initially used a pull-based execution model
  - "Vector Volcano"
- Every operator implements **`GetChunk`**

- Query starts by calling **`GetChunk`** on the root
- Nodes recursively call **`GetChunk`** on children

Simplified Projection Example

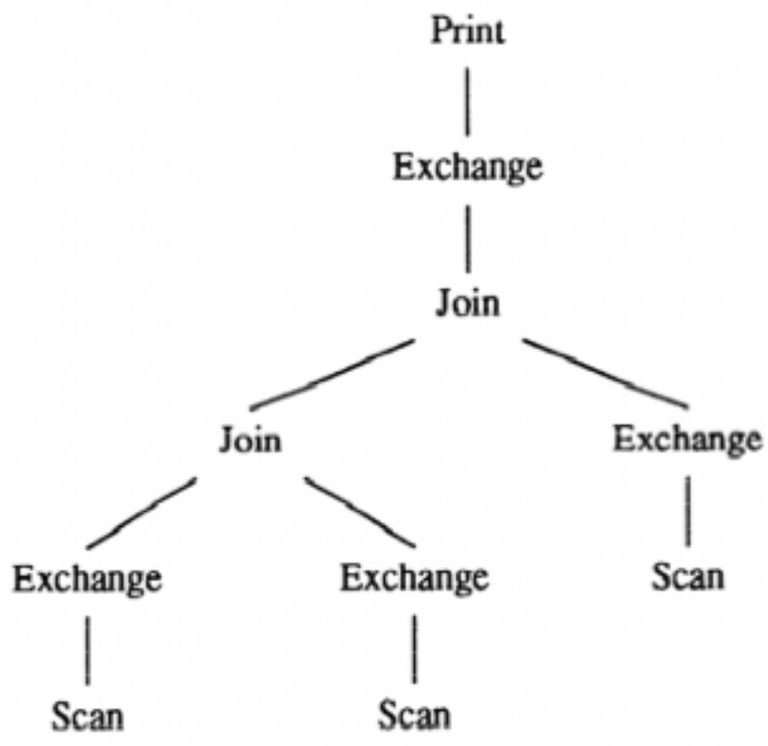
```
void Projection::GetChunk(DataChunk &result) {
    // get the next chunk from the child
    child->GetChunk(child_chunk);
    if (child_chunk.size() == 0) {
        return;
    }

    // execute expressions
    executor.Execute(child_chunk, result);
}
```

- **In this model:**
- Single-threaded execution is straightforward
- Multi-threaded not so much…
- How do you make operators parallelism-aware?

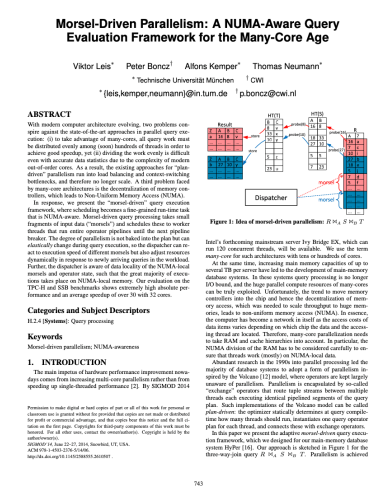
Pipeline Parallelism

- Exchange operator
- Optimiser splits query plan into partitions
- Partitions can be executed independently
- **Problems:**
  - Load imbalance issues
  - Plan explosion
  - Added materialization costs



Pipeline Parallelism

- Morsel-Driven Parallelism
- Individual operators are parallelism-aware
- Query is divided into pipelines
- Pipelines are executed in parallel


Morsel-Driven Parallelism: A NUMA-Aware Query Evaluation Framework for the Many-Core Age

Viktor Leis* Peter Boncz† Alfons Kemper* Thomas Neumann*

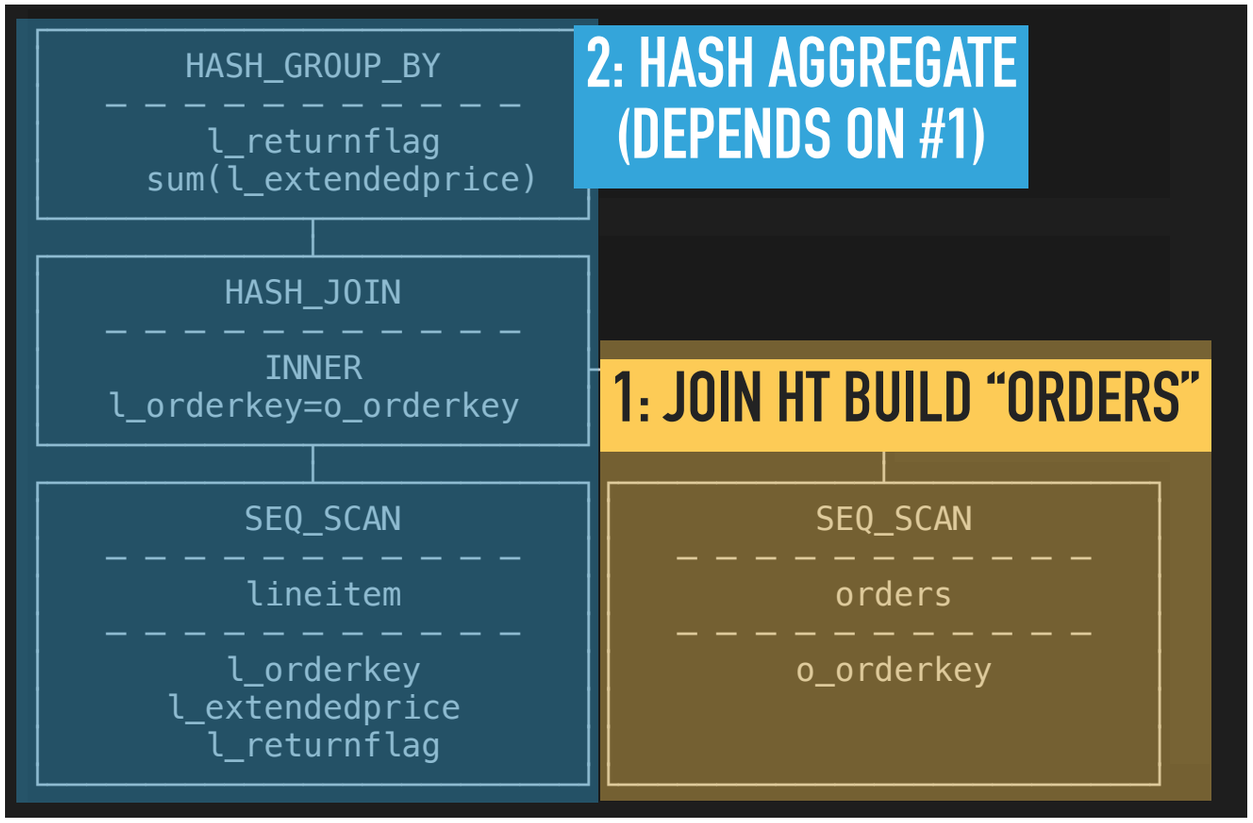
* Technische Universität München † CWI

[2014] Morsel-Driven Parallelism: A NUMA-Aware Query Evaluation Framework for the Many-Core Age

Viktor Leis et al.

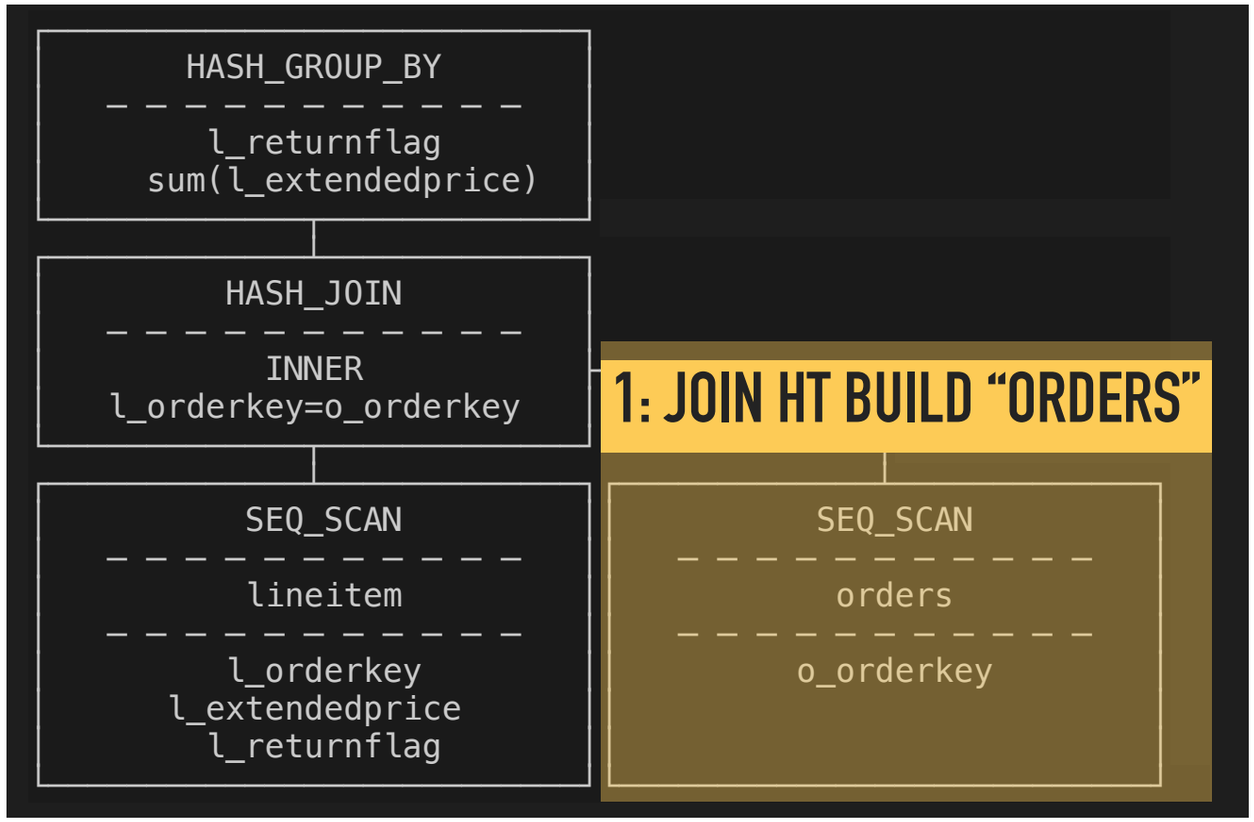
Pipeline Parallelism


```
SELECT SUM(l_extendedprice)
FROM lineitem
JOIN orders
ON (l_orderkey=o_orderkey)
GROUP BY l_returnflag;
```



Pipeline Parallelism

- Contention happens **at endpoints**
  - **Source:** Scan of orders
  - **Sink:** HT build of join



- Use **parallelism-aware** operators at endpoints
- Other operators (HT probe, projection, filter, etc…) don't need to be aware

- **Sink Interface**
- Sinks can define **global** and **local** states
- **`Sink`** is called until all data is exhausted
- **`Combine`** is called (once per thread)
- **`Finalize`** is called (once)

```
void Sink(
    ExecutionContext &context,
    GlobalSinkState &gstate,
    LocalSinkState &lstate,
    DataChunk &input);
void Combine(
    ExecutionContext &context,
    GlobalSinkState &gstate,
    LocalSinkState &lstate);
void Finalize(
    ClientContext &context,
    GlobalSinkState &gstate);
```

Simplified Hash Join Example

```
void HashJoin::Sink(DataChunk &input) {
    // build the hash table
    BuildHashTable(input);
}

void HashJoin::GetChunk(DataChunk &result) {
    // probe the hash table
    left_child->GetChunk(child_chunk);
    ProbeHashTable(child_chunk, result);
}
```

Pipeline Parallelism

- Pipelines are run by pulling from child of sink
- After child is exhausted, call **`Combine/Finalize`**
- Mix of push/pull: sink is push, rest is pull…

```
void RunPipeline() {
    // fetch data from child of sink
    while(sink->child->GetChunk(child_chunk)) {
        sink->Sink(child_chunk, ...);
    }
    // finished: combine
    sink->Combine(...);
    if (all_threads_finished) {
        // all threads are finished: finalize sink
        sink->Finalize(...)
        ScheduleNextPipeline();
    }
}
```

- How do we partition **Sources**?
- Not as straightforward…
- Sources are located at the bottom of the pipeline

Pipeline Parallelism

- Set up a **tasks** in thread context
- Tasks define how the scan is partitioned
- Read those tasks in the **`GetChunk`**

```
void TableScan::GetChunk() {
    // check if there is a task scheduled for this operator
    table.ScanTask(thread_context.tasks.find(this));
}
```

- This mostly works
- Problems:
  - Data flow duplicated in every operator
  - No clean interface for source parallelism
  - How to parallelize **UNION** nodes?
  - How to parallelize **FULL/RIGHT** outer joins?
  - Scan Sharing?
  - Async I/O?

Push-Based Execution

- What is push-based execution?

- Our previous model was **pull-based:**
  - **`GetChunk`** called when an operator requires data

- **Push-based** is the other way around
  - Push data into operators

- **Sink interface** is already push-based!

- **Push-Based** moves data flow **out of operators**
  - Data flow is handled in central location
- Simplifies implementation of operators
  - But reduces flexibility!

- Define **Operator** and **Source** interface

- **Operator** processes data
  - Projection, Filter, Hash Probe, …
- **Source** emits data
  - Table scan, aggregate HT scan, ORDER BY scan, etc

Operator Interface

```
OperatorResultType Execute(
    ExecutionContext &context,
    DataChunk &input,
    DataChunk &chunk,
    OperatorState &state);
```

- **Execute** takes an input chunk, and outputs another chunk

- **Projection** is straightforward

```
void Projection::Execute(DataChunk &input, DataChunk &result)
{
    executor.Execute(input, result);
}
```

- **Hash Probe** seems straightforward…

```
void HashJoin::Execute(DataChunk &input, DataChunk &result) {
    Probe(input, result);
}
```

- How do we handle multiple matches per tuple?
  - 1 input entry can lead to many output entries…
- Operators need a way of signalling they are not done processing the input

- **OperatorResultType** is used for this

```
enum OperatorResultType {
    NEED_MORE_INPUT,
    HAVE_MORE_OUTPUT,
    FINISHED
};
```

- **`NEED_MORE_INPUT`**: Operator will be called with a new input chunk
- **`HAVE_MORE_OUTPUT`**: Operator will be called with the same input chunk
- **`FINISHED`**: The operator will not be called again, terminates the pipeline

```
enum OperatorResultType {
    NEED_MORE_INPUT,
    HAVE_MORE_OUTPUT,
    FINISHED
};
```

- **`FINISHED`** required to interrupt execution
  - Happens naturally in a pull-based model
  - e.g. **`LIMIT`** in pull-based simply stops pulling
- In push-based, we need to signal to the execution loop that we finished early

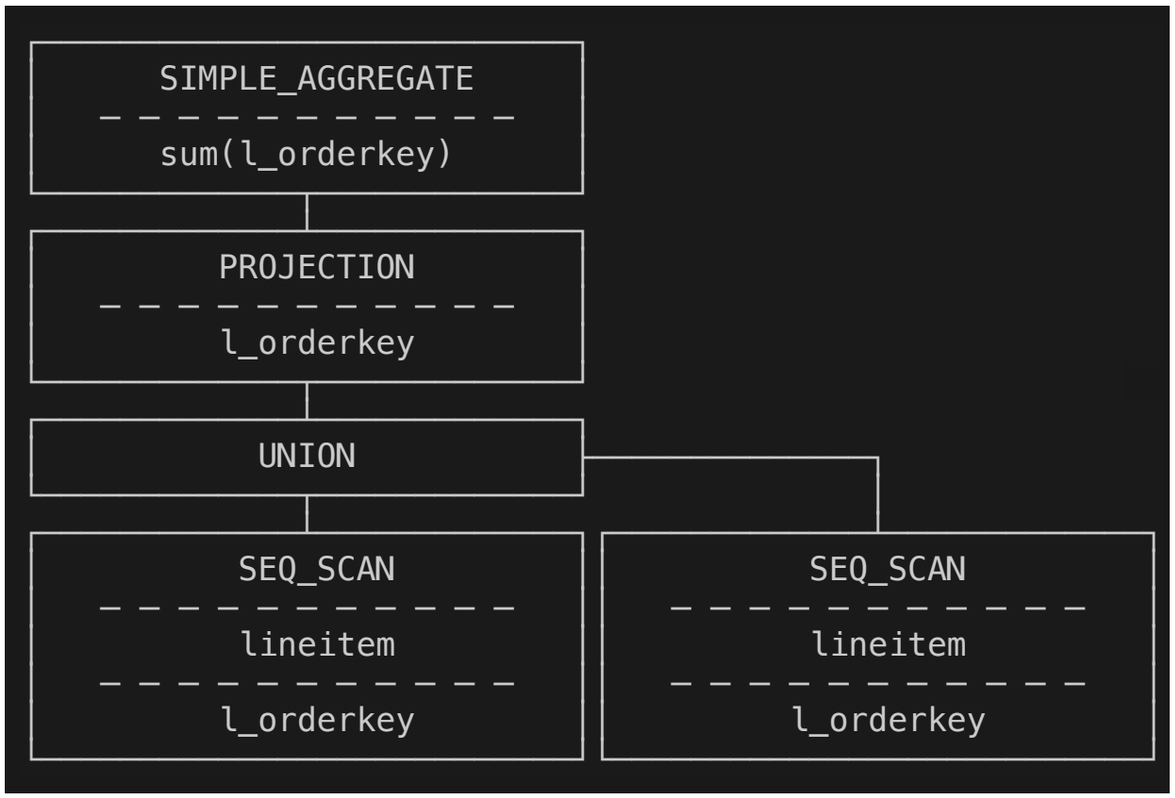
- **Source Interface**
- Similar to **Sink** interface
- **Global** and **local** states
- **`GetData`** is called until no more data remains
  - Or pipeline is cancelled earlier

```
void GetData(
    ExecutionContext &context,
    DataChunk &chunk,
    GlobalSourceState &gstate,
    LocalSourceState &lstate);
```

Pipeline Events

Pipeline Events


```
SELECT SUM(l_orderkey)
FROM
(
   SELECT *
   FROM lineitem
   UNION ALL
   SELECT *
   FROM lineitem
)
```



- **UNION nodes**
- How do we execute unions?

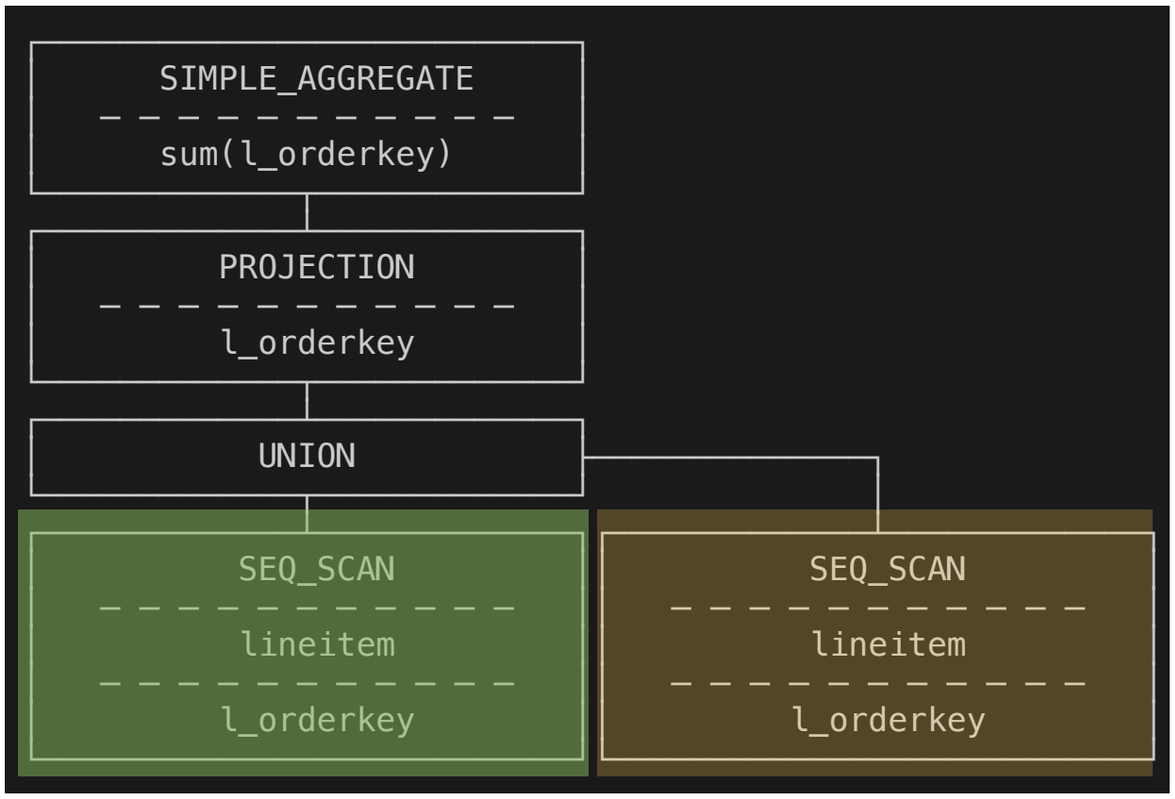
- **Pull-Based:** Easy, we control the flow

```
void Union::GetChunk(DataChunk &result) {
    if (!left_done) {
        left_child->GetChunk(result);
        if (result.size() > 0) {
            return;
        }
        left_done = true;
    }
    right_child->GetChunk(result);
}
```

- How do we do it **push-based**?

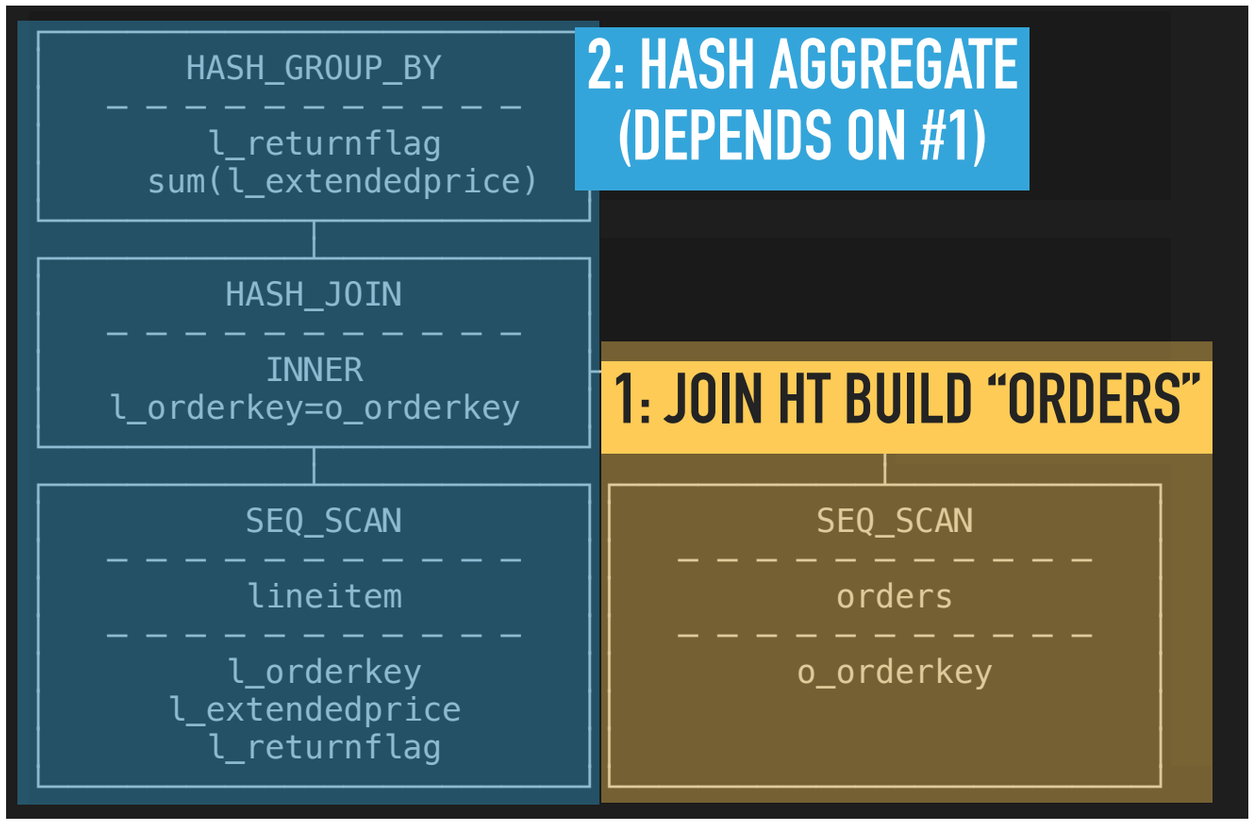
Pipeline Events


```
SELECT SUM(l_orderkey)
FROM
(
   SELECT *
   FROM lineitem
   UNION ALL
   SELECT *
   FROM lineitem
)
```

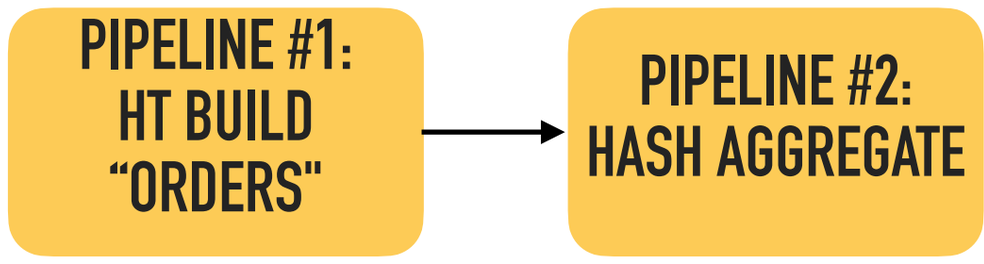


- **Push-Based Union**
- Create two pipelines with same sink
  - Or more, if there are more unions
- **`Sink::Finalize`** only after **all** pipelines are done!

Pipeline Scheduling



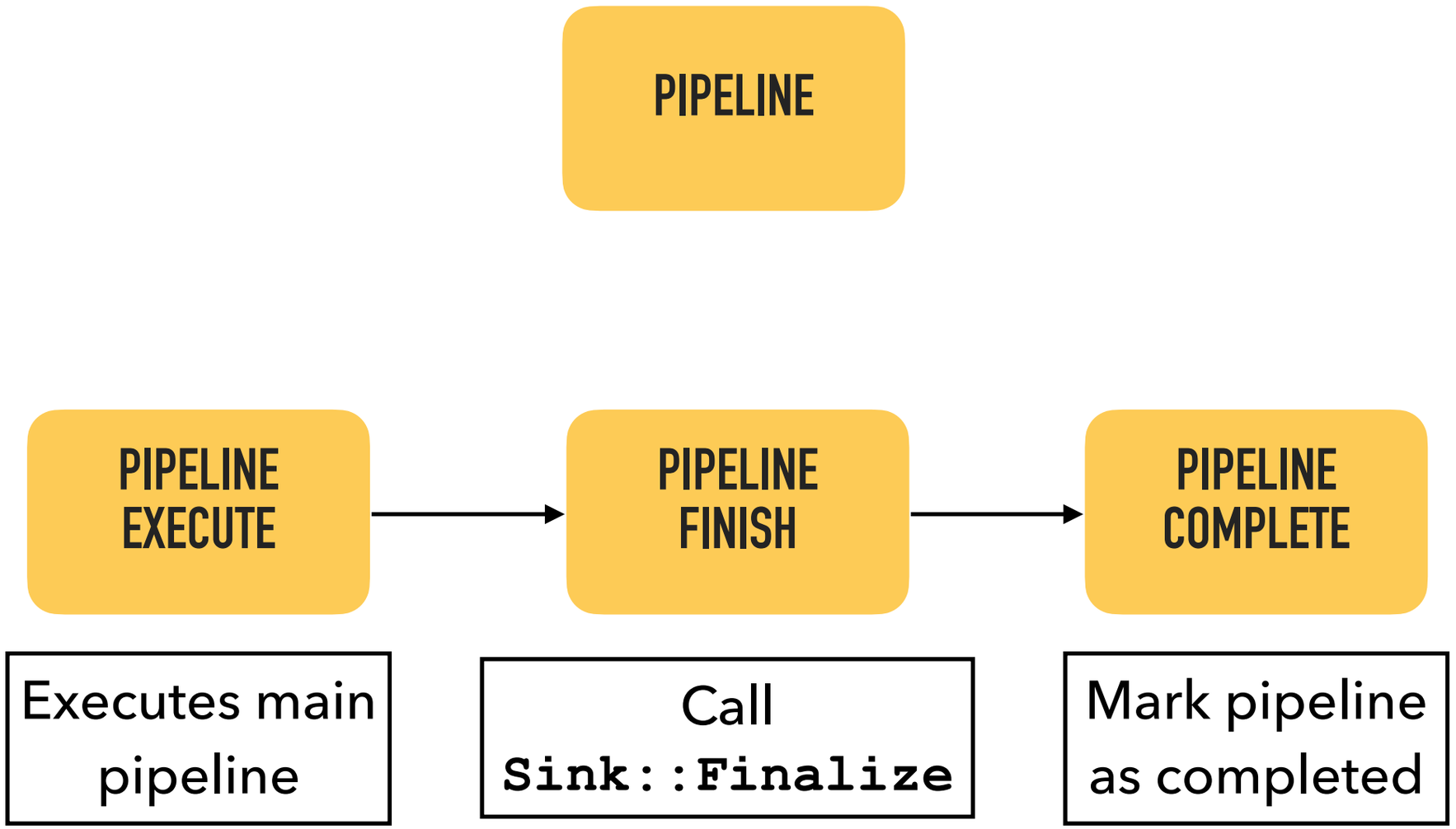

```
SELECT SUM(l_extendedprice)
FROM lineitem
JOIN orders
ON (l_orderkey=o_orderkey)
GROUP BY l_returnflag;
```



- How do we handle the **Union** case here?

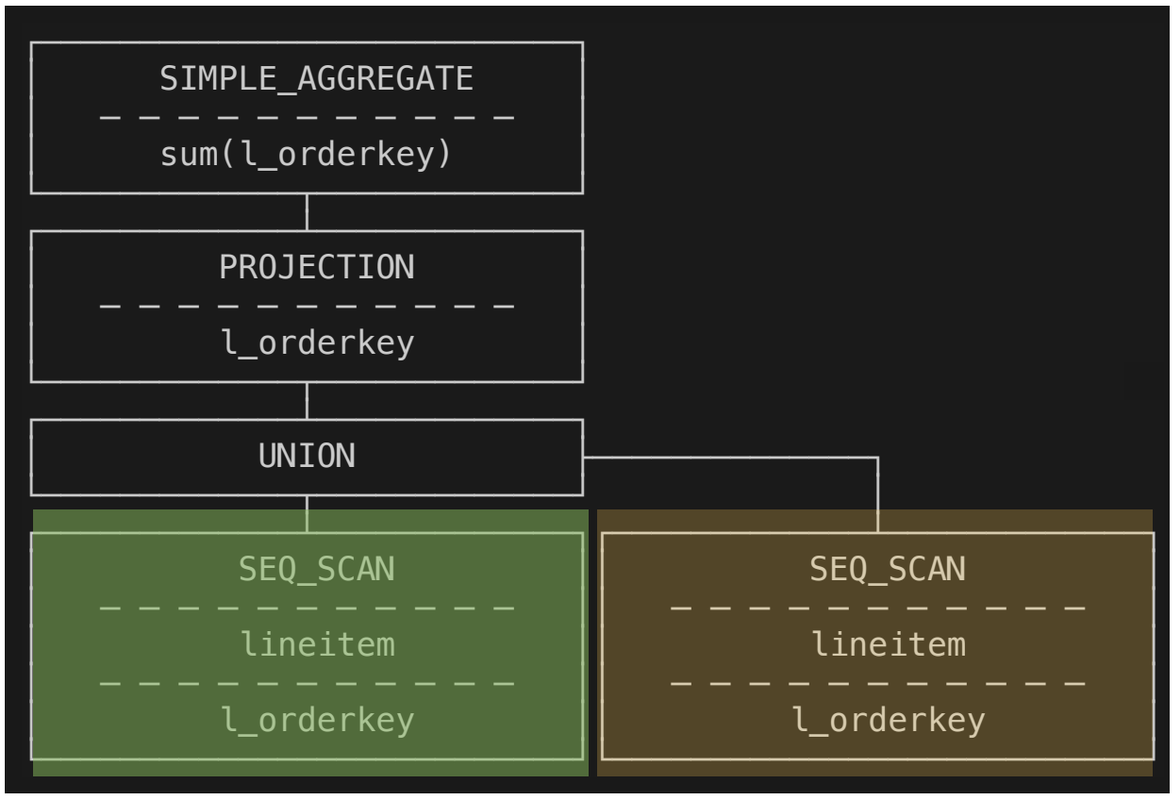
Pipeline Events

- Split up **Pipeline** into **Events**
- Schedule those **Events**

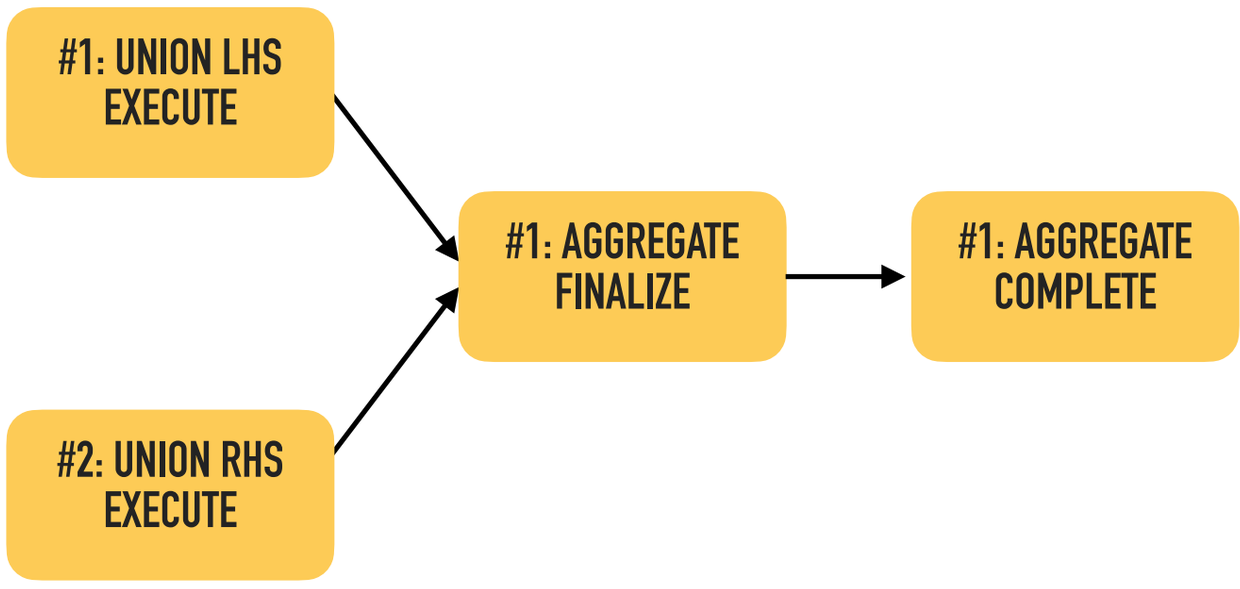


Pipeline Events


```
SELECT SUM(l_orderkey)
FROM
(
   SELECT *
   FROM lineitem
   UNION ALL
   SELECT *
   FROM lineitem
)
```

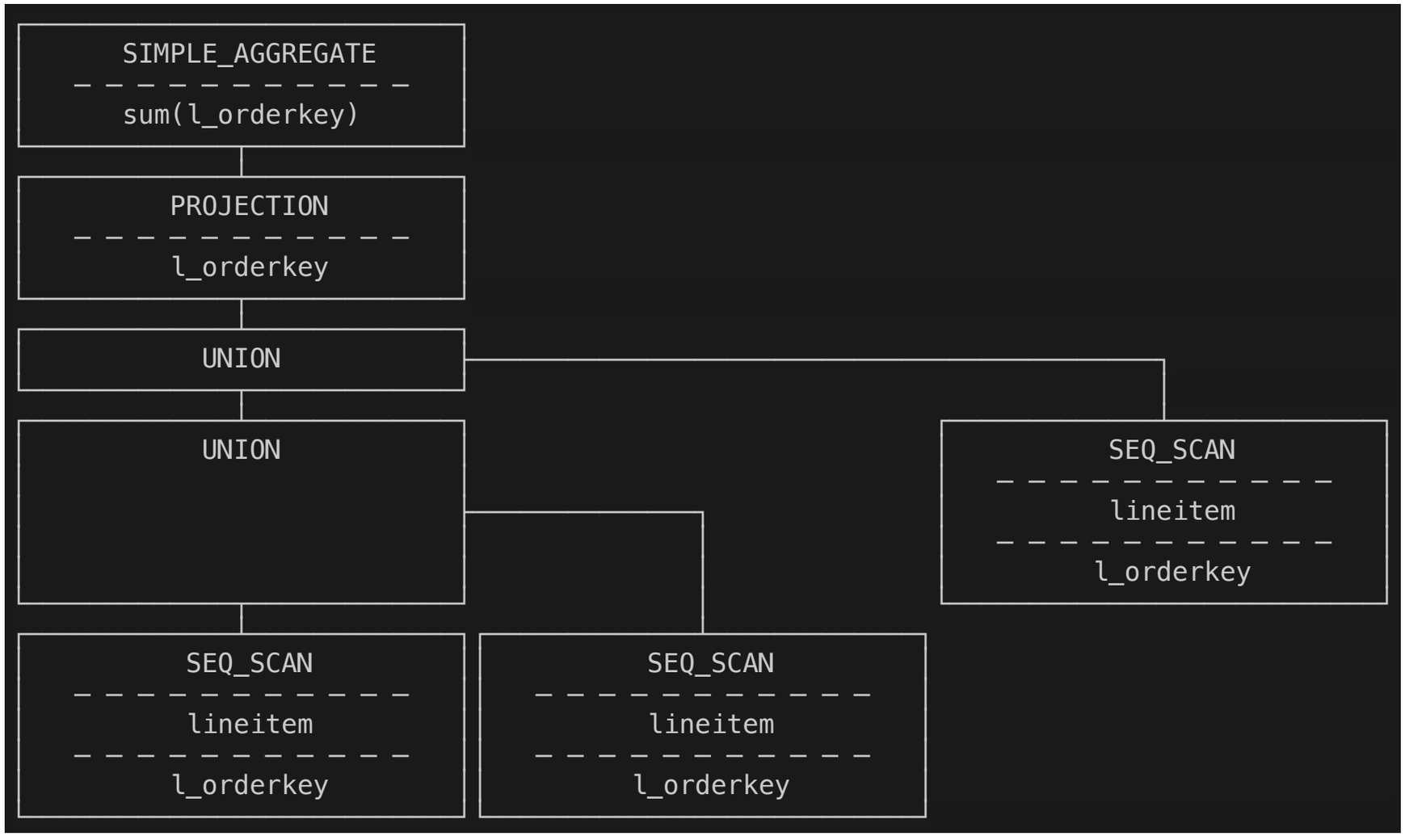


Now we can schedule multiple unions that will call Finalize once

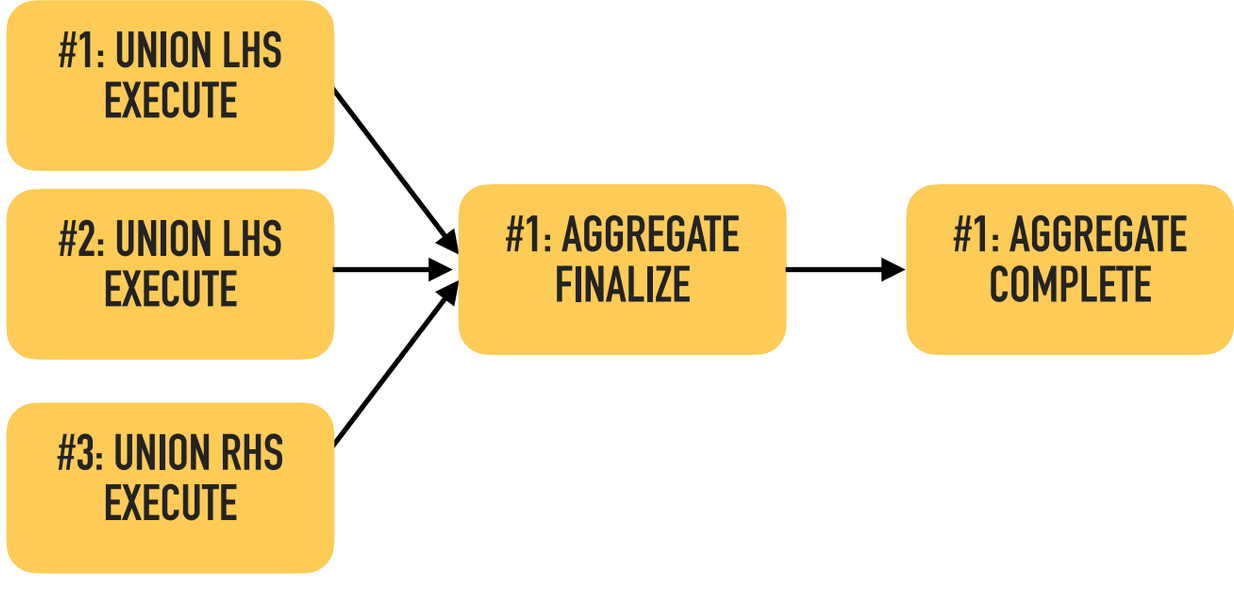


Pipeline Events


```
SELECT SUM(l_orderkey)
FROM
(
   SELECT *
   FROM lineitem
   UNION ALL
   SELECT *
   FROM lineitem
   UNION ALL
   SELECT *
   FROM lineitem
)
```



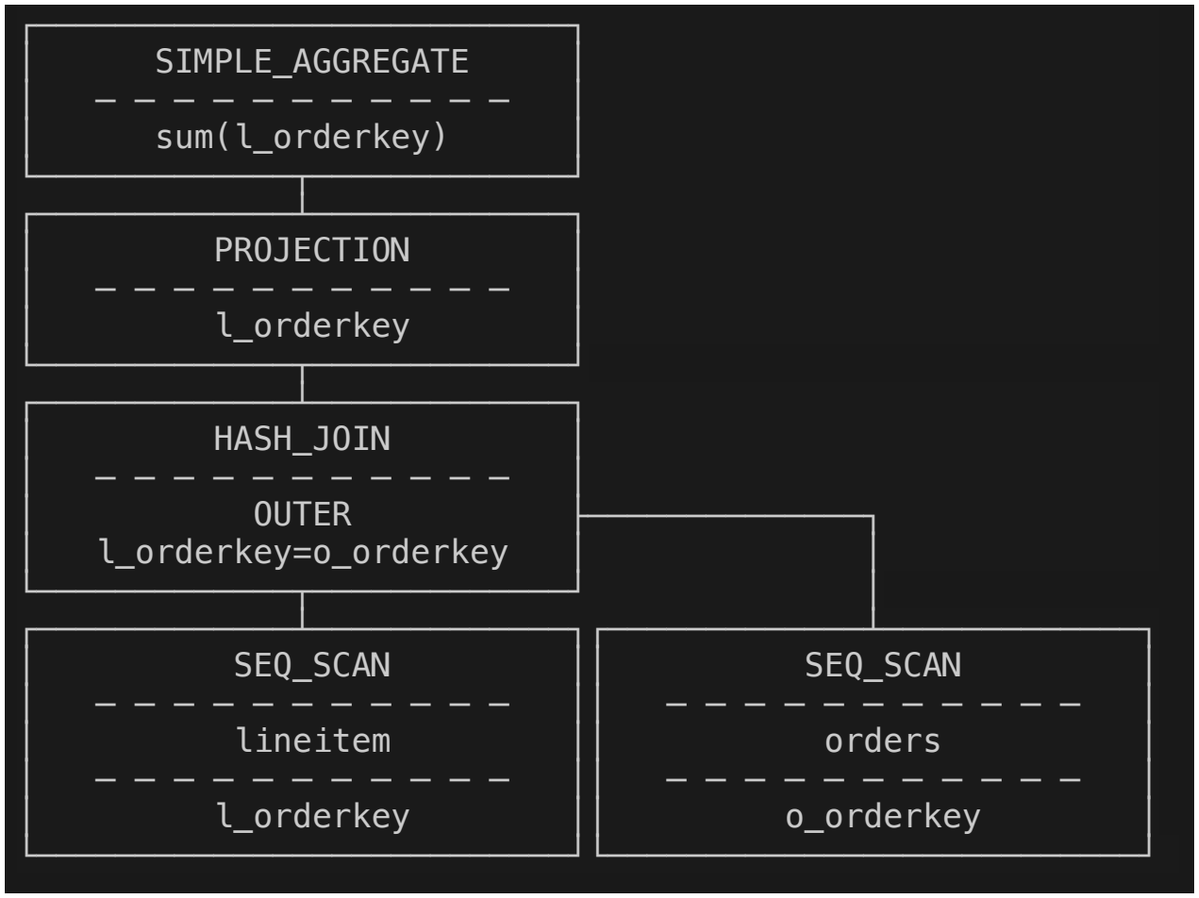
Can stack multiple unions

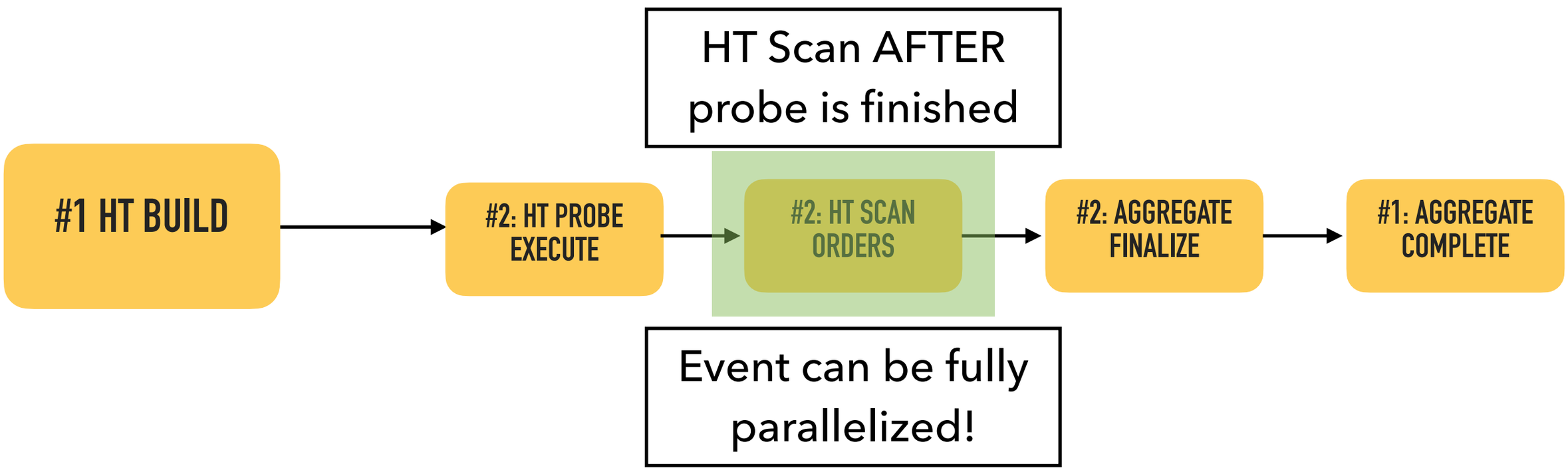


- **Full/Right Outer Joins** have similar challenge
- Three phases:
  - Build HT
  - Probe HT
  - Scan HT (after **ALL** probing is finished)

Pipeline Events

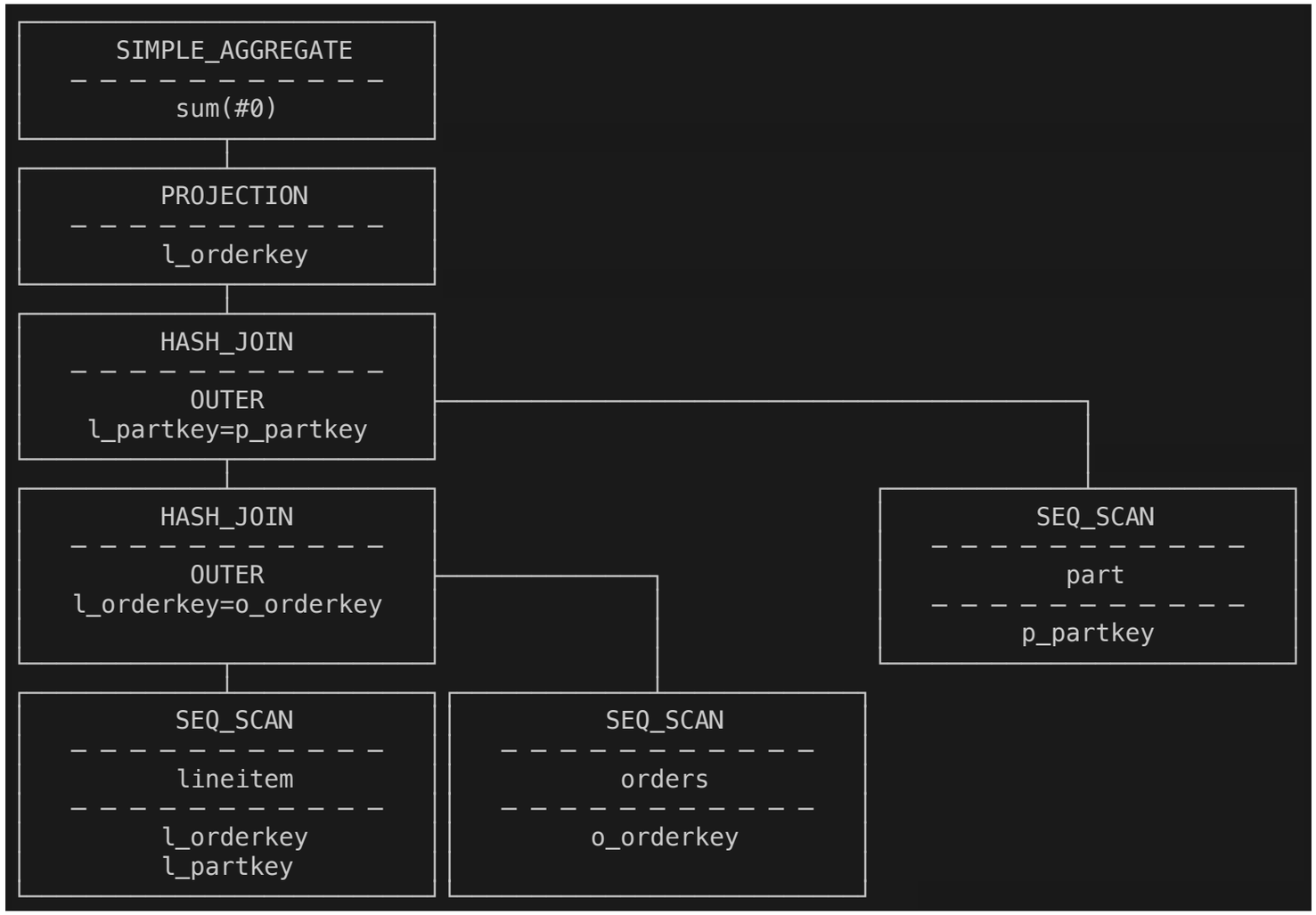

```
SELECT sum(l_orderkey)
FROM lineitem
FULL OUTER JOIN orders
    ON (l_orderkey=o_orderkey);
```

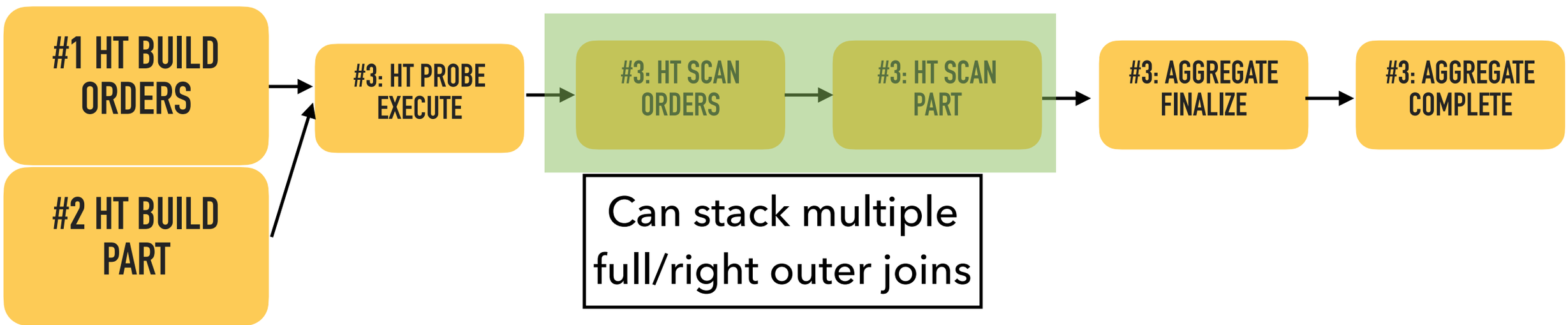




Pipeline Events


```
SELECT sum(l_orderkey)
FROM lineitem
FULL OUTER JOIN orders
    ON (l_orderkey=o_orderkey)
FULL OUTER JOIN part
    ON (l_partkey=p_partkey);
```



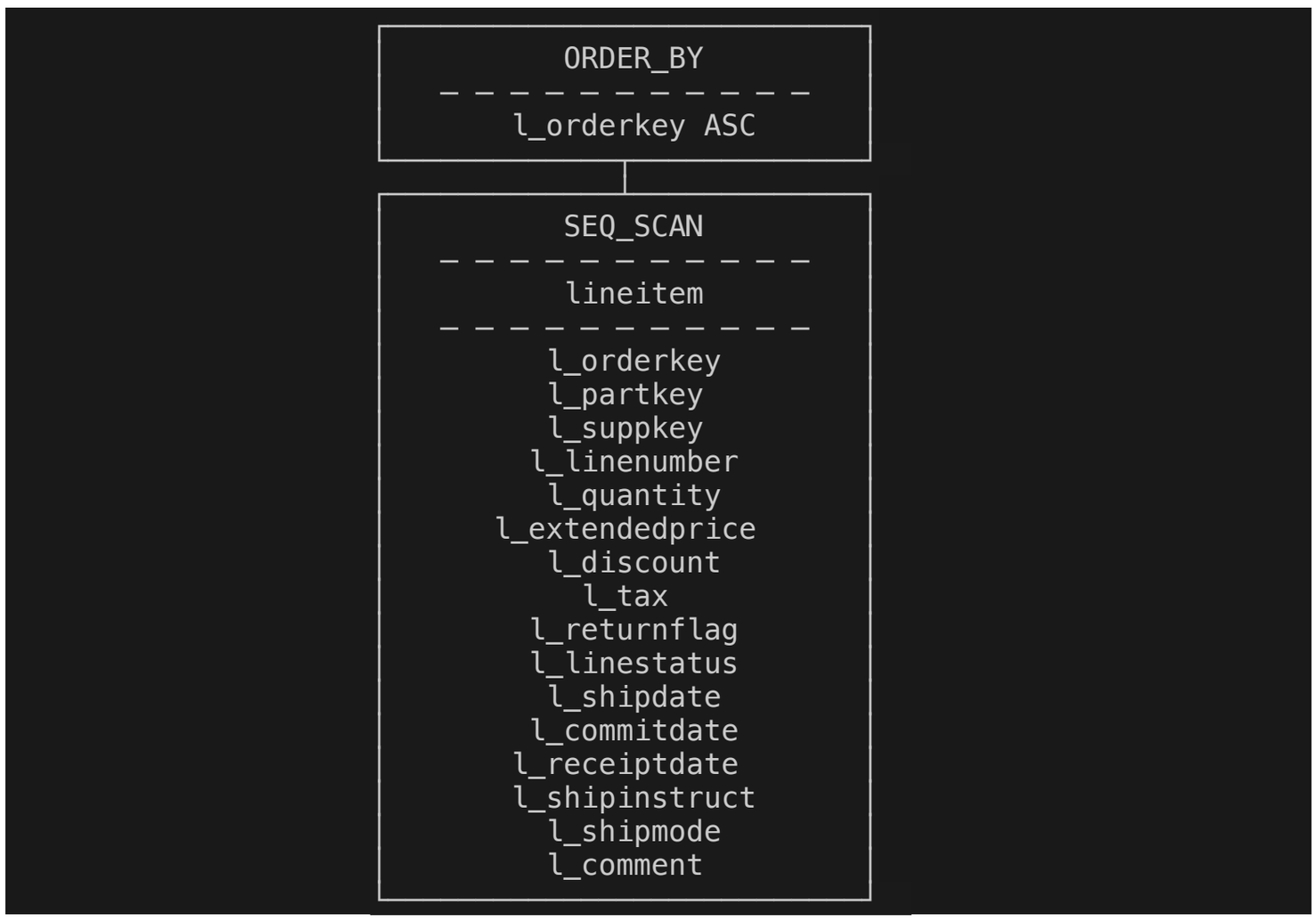


Pipeline Events

- Sinks often have an expensive Finalize step
  - e.g. **order by -** merging sorted segments
- Need to be executed in parallel

Pipeline Events


```
SELECT *
FROM lineitem
ORDER BY l_orderkey;
```

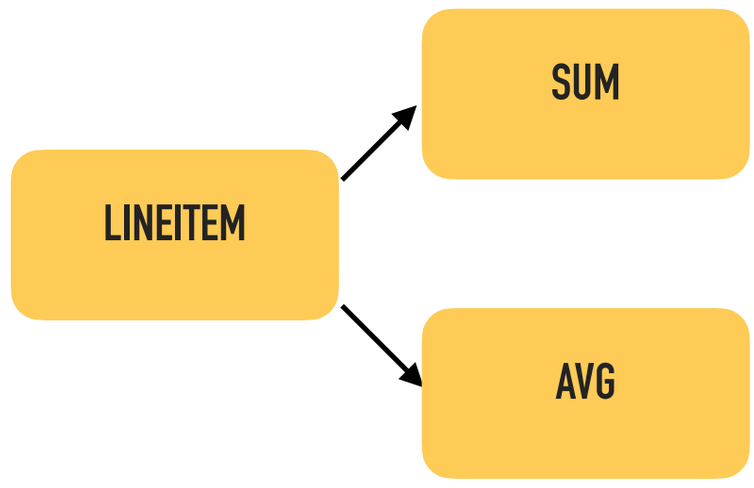


`Sink::Finalize` can schedule additional events

Future Work

- **Scan Sharing (TODO)**
- Detect pipelines that have the same source
- Scan once, sink into multiple pipelines

```
SELECT SUM(l_orderkey)
FROM lineitem
UNION ALL
SELECT AVG(l_orderkey)
FROM lineitem;
```



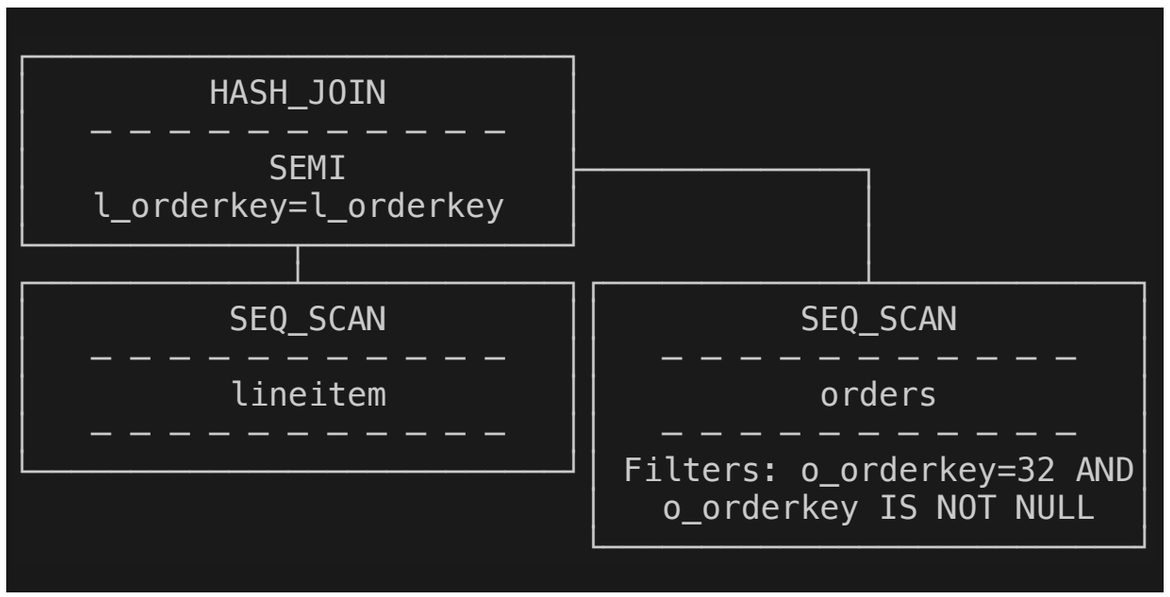
- Complicated by **projection & filter pushdown**
  - Disjoint projections -> scan sharing not useful*

* Unless we are scanning a row-store

- **Async I/O (TODO)**
- Current scans are still pull-based
- Fine for in-memory data
- Reading from disk/http/etc -> stall on read
- Async I/O solves this by pushing I/O to background threads
- When I/O completes, push data into pipeline

- **Hybrid Early/Late Materialization**
- Async I/O prefetches all required columns
- Early materialization
- Late materialization at times preferable
  - e.g. query with selective predicate on one column

Async I/O




```
SELECT *
FROM lineitem
WHERE EXISTS
    (SELECT *
     FROM orders
     WHERE l_orderkey=o_orderkey
       AND o_orderkey=32);
```

- This query selects a few rows
  - But reads all columns of entire lineitem table
- **Early materialization**: read entire lineitem table
- **Late materialization**: read l_orderkey column and few rows from other columns

- **Hybrid Early/Late Materialization**
- Lazy vectors enable hybrid of early/late materialization
- When a vector is first used, fetch data from disk

- Conflicts with Async I/O!
- **Potential solution**: Hybrid Async I/O
  - Prefetch with async I/O
  - Stop prefetching for a column if we detect column data is not required

That’s all folks!

Thanks for listening!