Mark Raasveldt & Pedro Holanda

DuckDB
an Embeddable Analytical RDBMS

Outline

- Internals at a Glance
- Query processing pipeline
- Query execution
- Hands-On

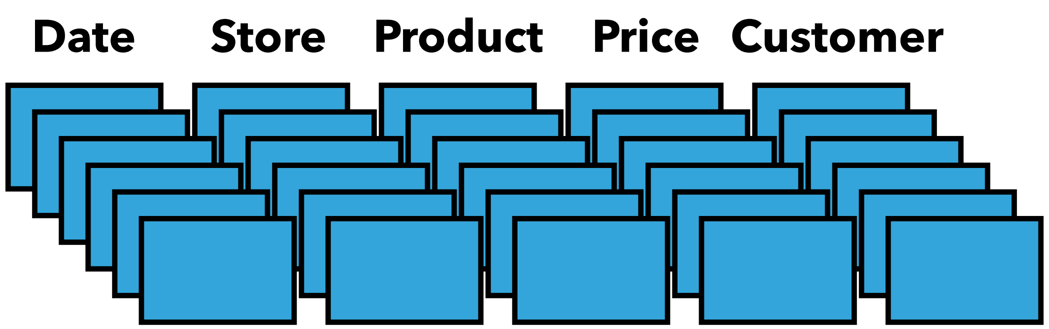
Outline

- **Before we start:** any Windows users here?
- If you do not have Visual Studio
  Download the community edition:
- https://visualstudio.microsoft.com/vs/community/
- And CMake:
- https://cmake.org/download/
- This is needed for the practicum!

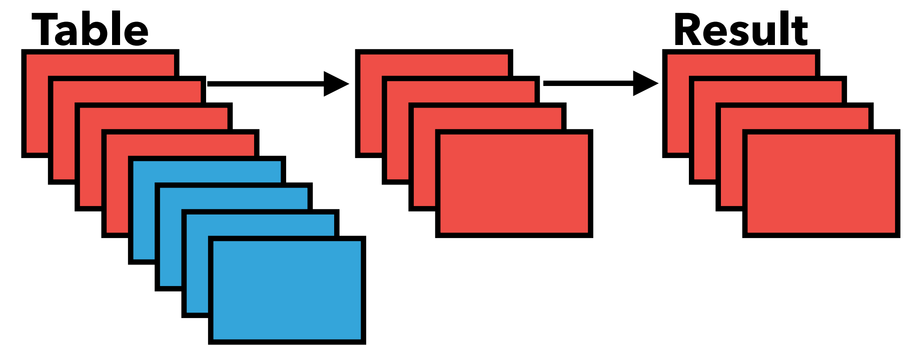
Internals at a Glance

Internals at a Glance

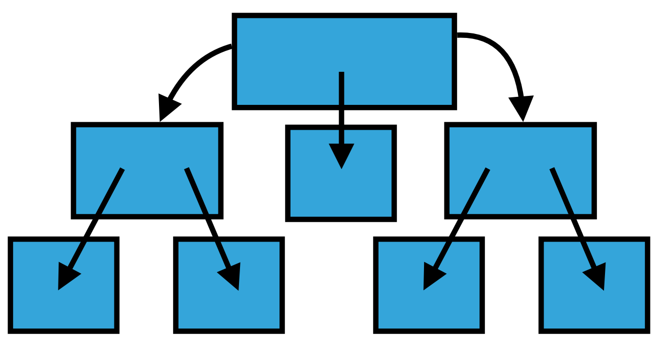
Column-Store



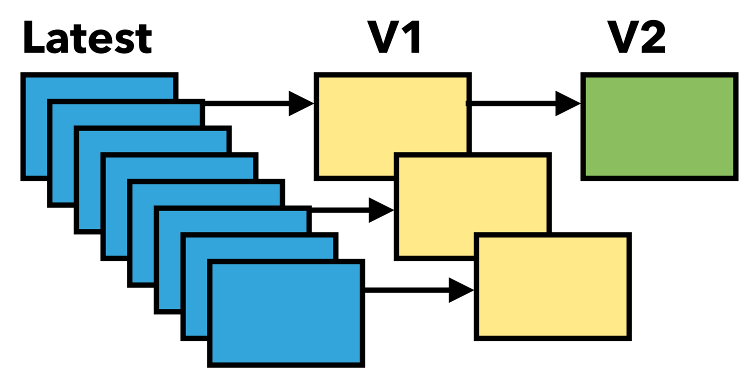
Vectorized Processing



ART Index



Multi-Version Concurrency Control



Single-File Storage

database.db

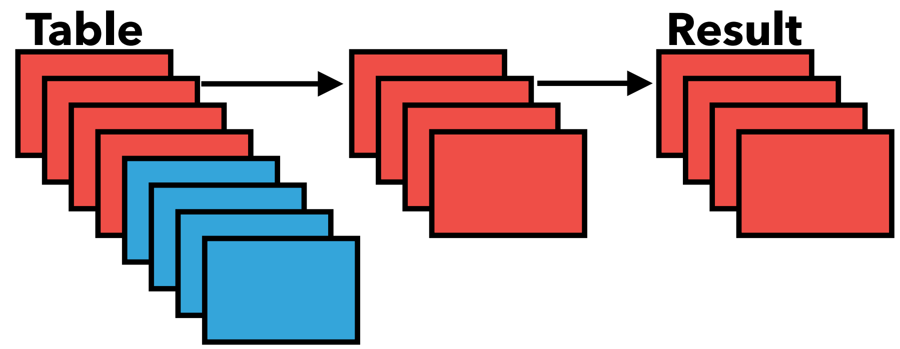
Parser

CWI

Internals at a Glance

Column-Store

Vectorized Processing



ART Index

Multi-Version Concurrency Control

Single-File Storage

database.db

Parser

Query Processing Pipeline

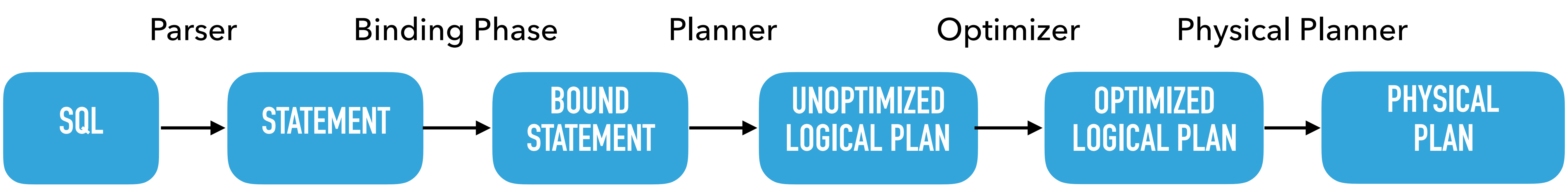
- **Life of a query**
- How does the system go from query to result?
- We will focus on the following query:

```
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

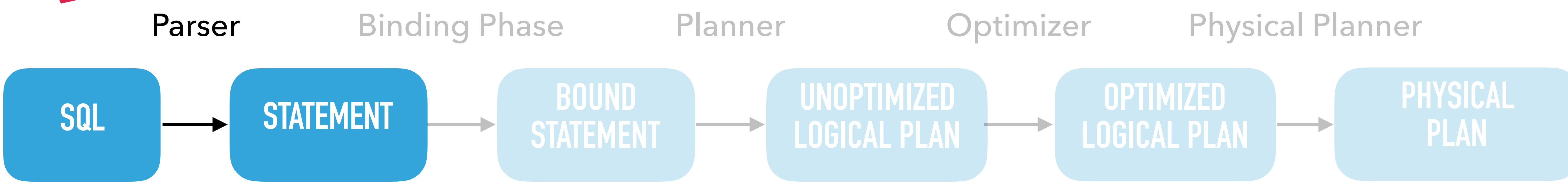
- **Aggregate:** `COUNT(*)`
- **Implicit join:** `lineitem, orders` **on** `orderkey`
- **Filters:** `o_orderstatus='X'` **and** `l_tax>50`

DuckDB

- DuckDB uses a typical pipeline for query processing



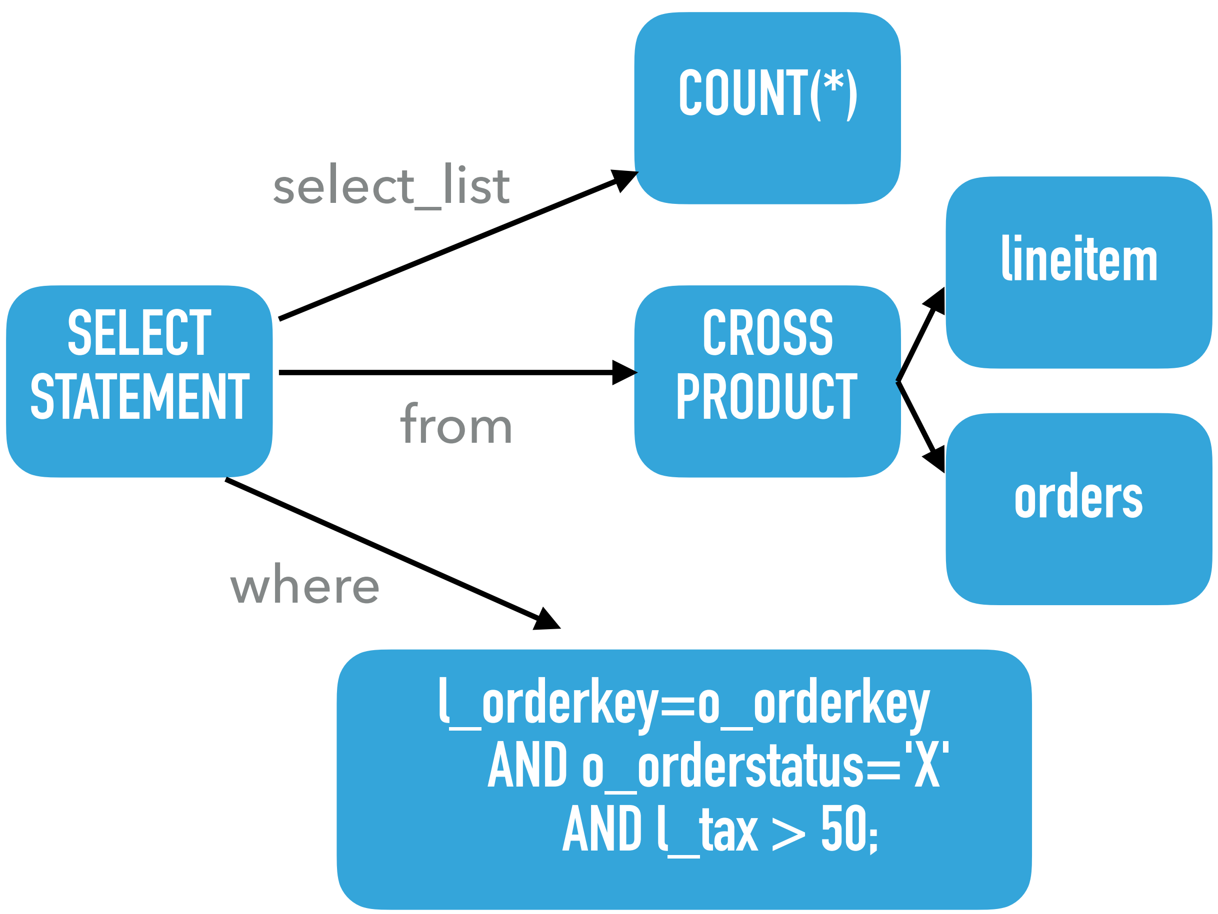
DuckDB



- Query is input into the system as a string
- The **lexer and parser** take the input string and convert it into a set of **statements**, **expressions** and **table references**
    - Note that this is not yet a query tree!
- We utilize the **Postgres parser** for this part

```sql
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

- The result of the **parsing** stage is the following:



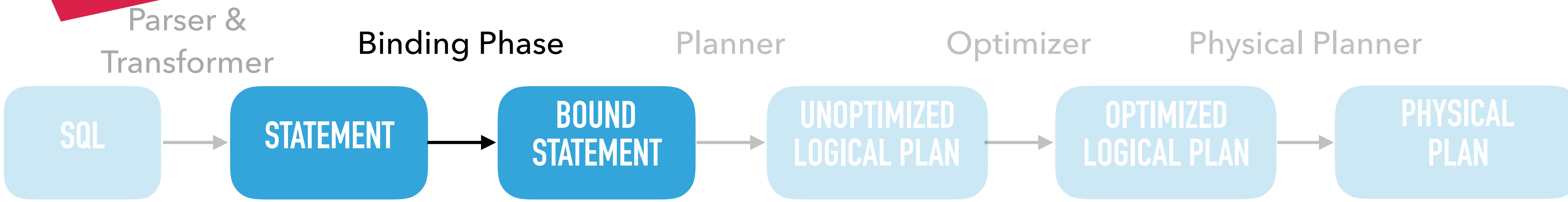

```sql
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

- In (pseudo) code, this is as follows:

```
class SelectStatement : Statement {
    vector<Expression*> select_list = { COUNT(*) }
    TableRef from_clause = CROSS_PRODUCT("lineitem", "orders");
    Expression *where_clause = "l_orderkey"="o_orderkey"
                                  AND "o_orderstatus"="X"
                                  AND "l_tax" > 50;
}
```

```
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

- Note: table/column names *are not resolved yet*
  - e.g. if **lineitem** table does not exist, no error will be thrown yet



- **Binding phase** has two purposes
  - Catalog lookup of table/column names
  - Type resolution of expressions
- Replace existing statement by **BoundStatement**

```
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

DuckDB

- Look up tables `lineitem` and `orders` tables
- Look up **columns** within these tables

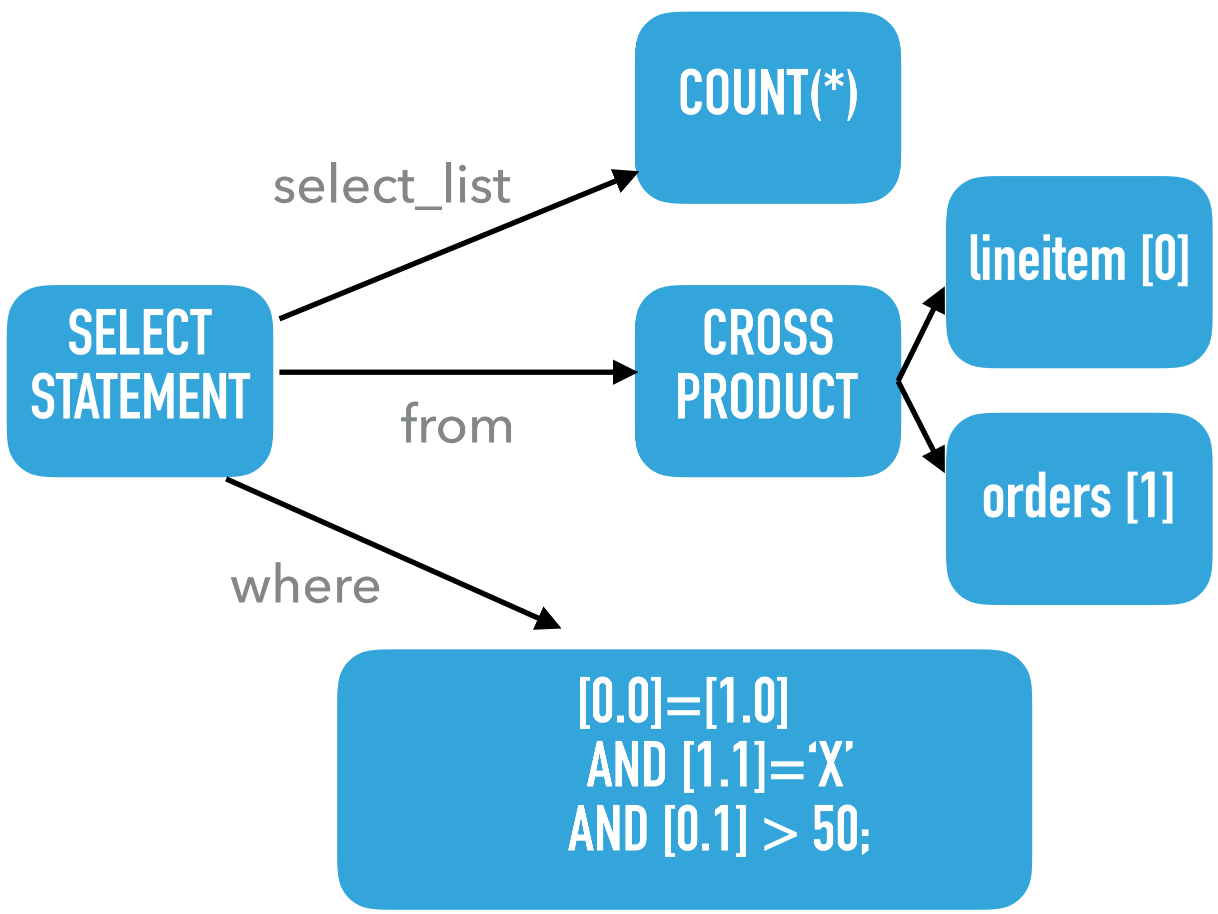


table index
lineitem: 0
orders: 1

column index
l_orderkey: 0
l_tax: 1

column index
o_orderkey: 0
o_orderstatus: 1

```sql
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

- Replace table names with **table indexes**
- Replace column names with **table+column** indexes

DuckDB

- **Type resolution:** look up the types from the tables
  - `l_orderkey : INTEGER`
  - `o_orderkey : INTEGER`
- `l_orderkey = o_orderkey : BOOLEAN`

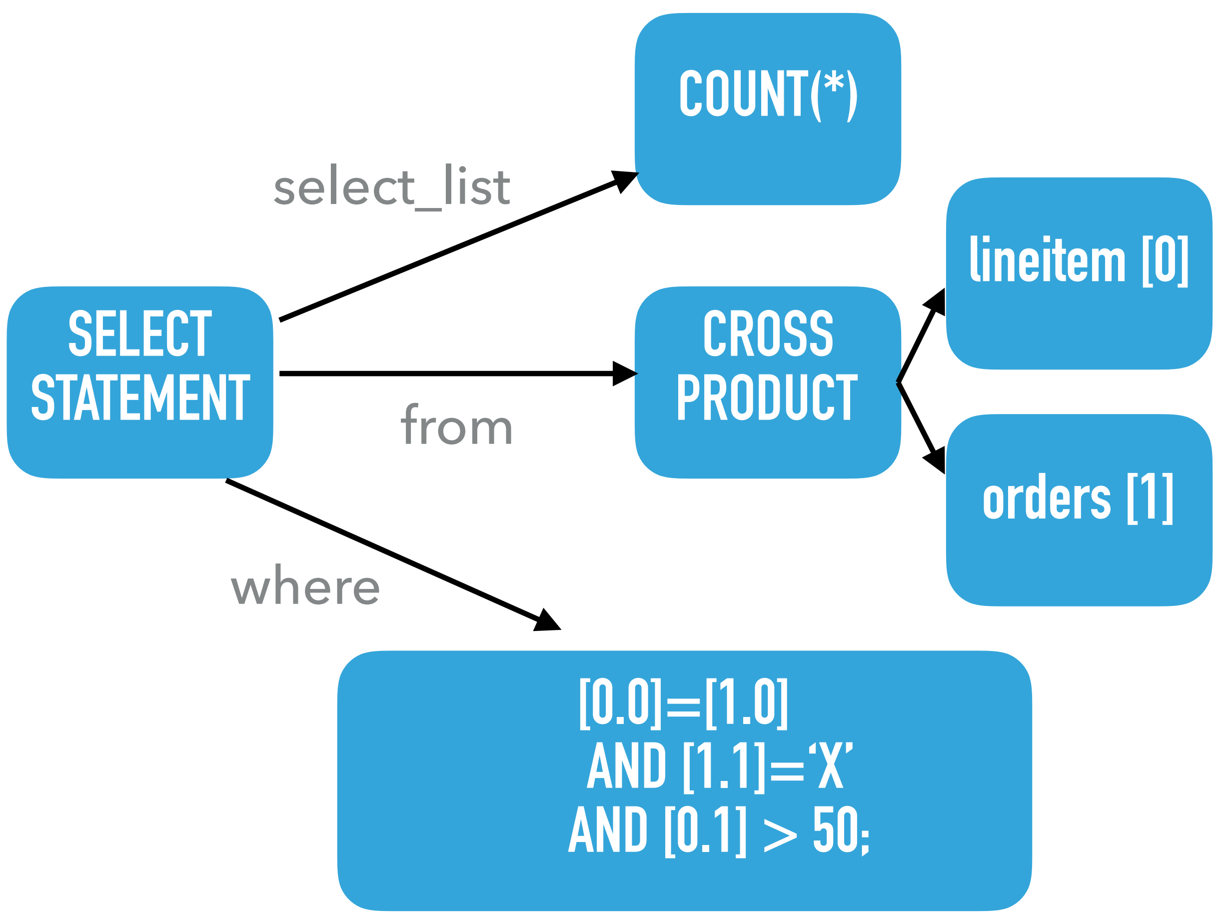


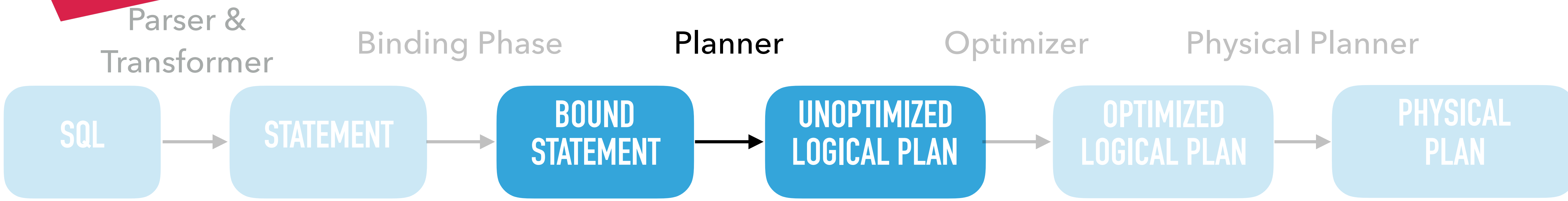
table index
lineitem: 0
orders: 1

column index
l_orderkey: 0
l_tax: 1

column index
o_orderkey: 0
o_orderstatus: 1

```
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

DuckDB



- **Planner**: Create **logical** query tree
- The logical query tree contains **logical operations**
  - Describes what to do, not how to do it
  - e.g. "`Join`", not "`HashJoin`" or "`MergeJoin`"

```sql
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

DuckDB

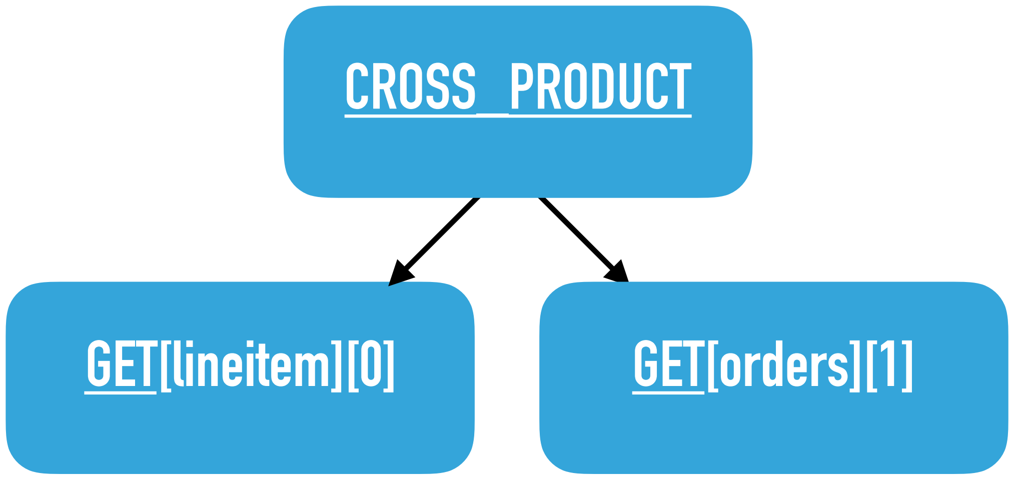
- Query tree starts with **tables**
- We have two tables: **lineitem** and **orders**
- These will result in two **LogicalGet** operations

GET[lineitem][0]   GET[orders][1]

```sql
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

DuckDB

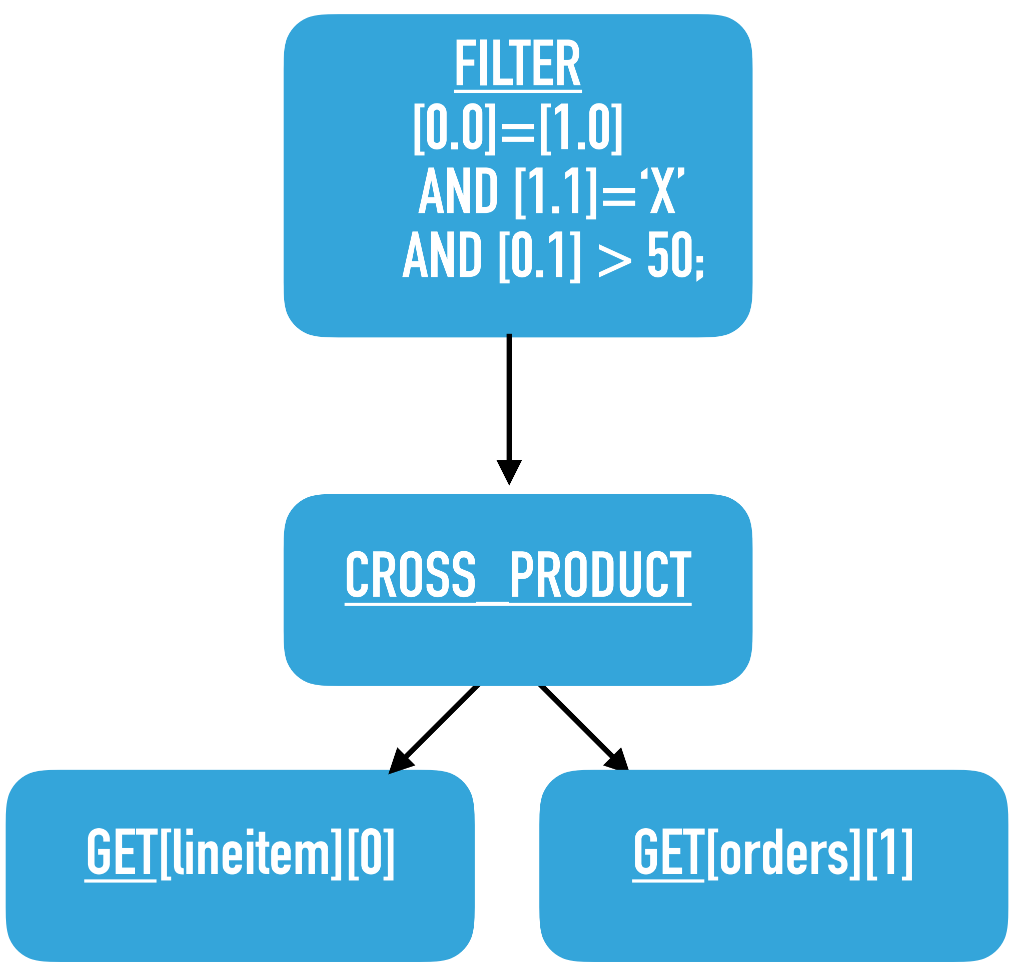
- The tables are combined with a **cross product**
  - There is no explicit join here
- The optimizer will later convert this into a join




```sql
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

DuckDB

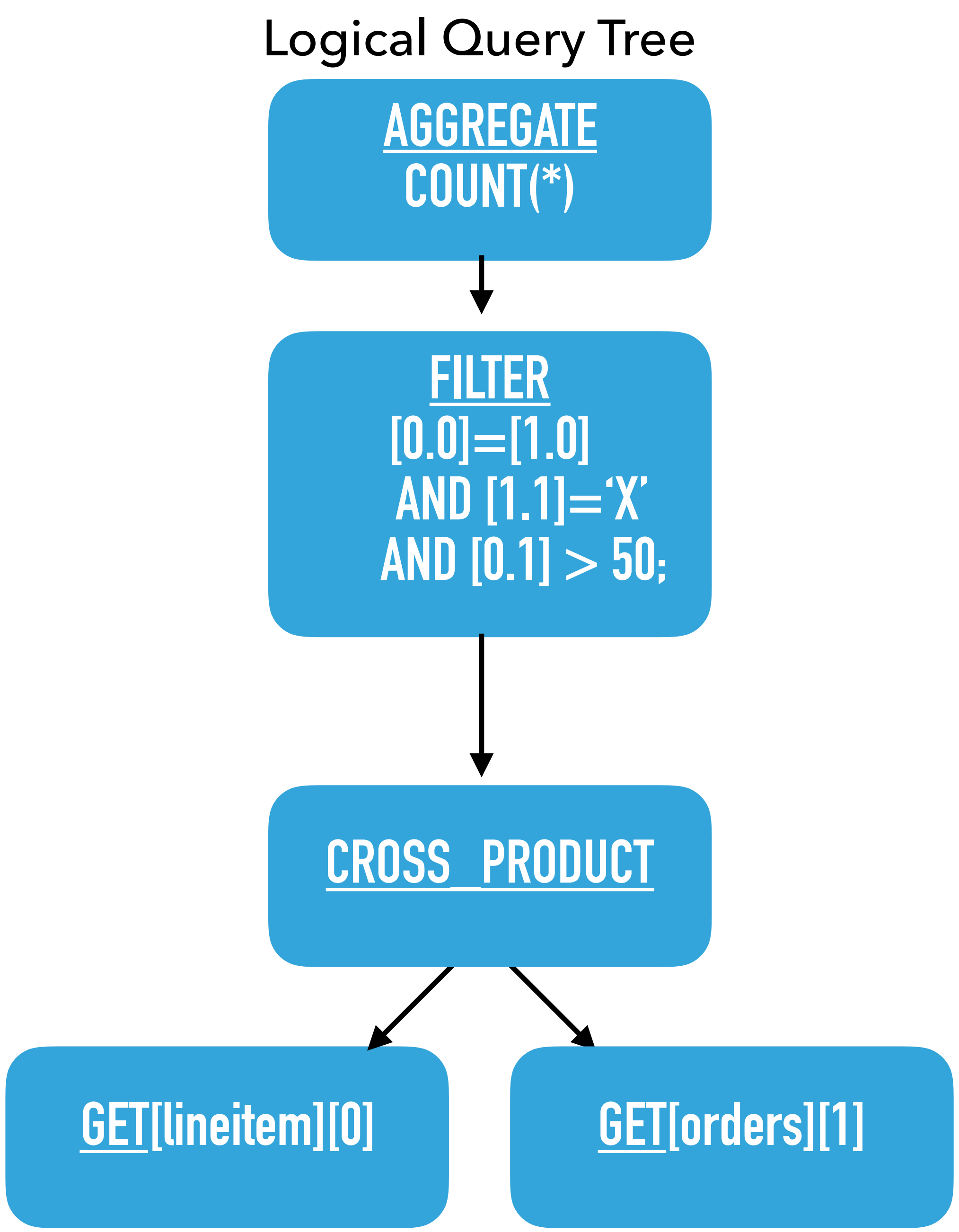
- After **Filter** is added
  - Filter has single big expression




```sql
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

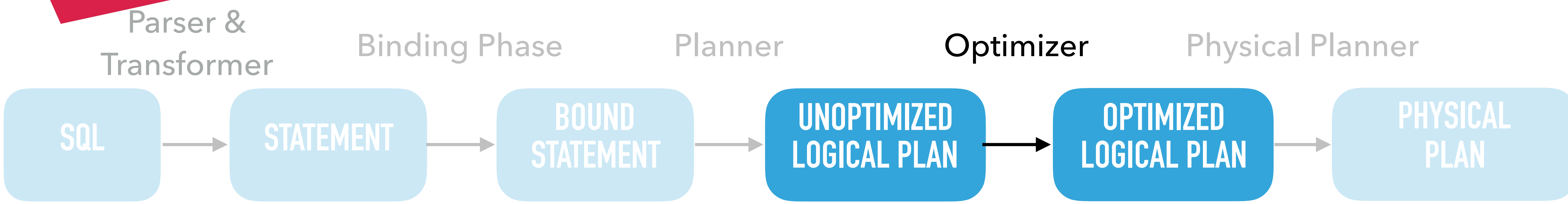
DuckDB

- Finally add aggregate computation




```sql
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

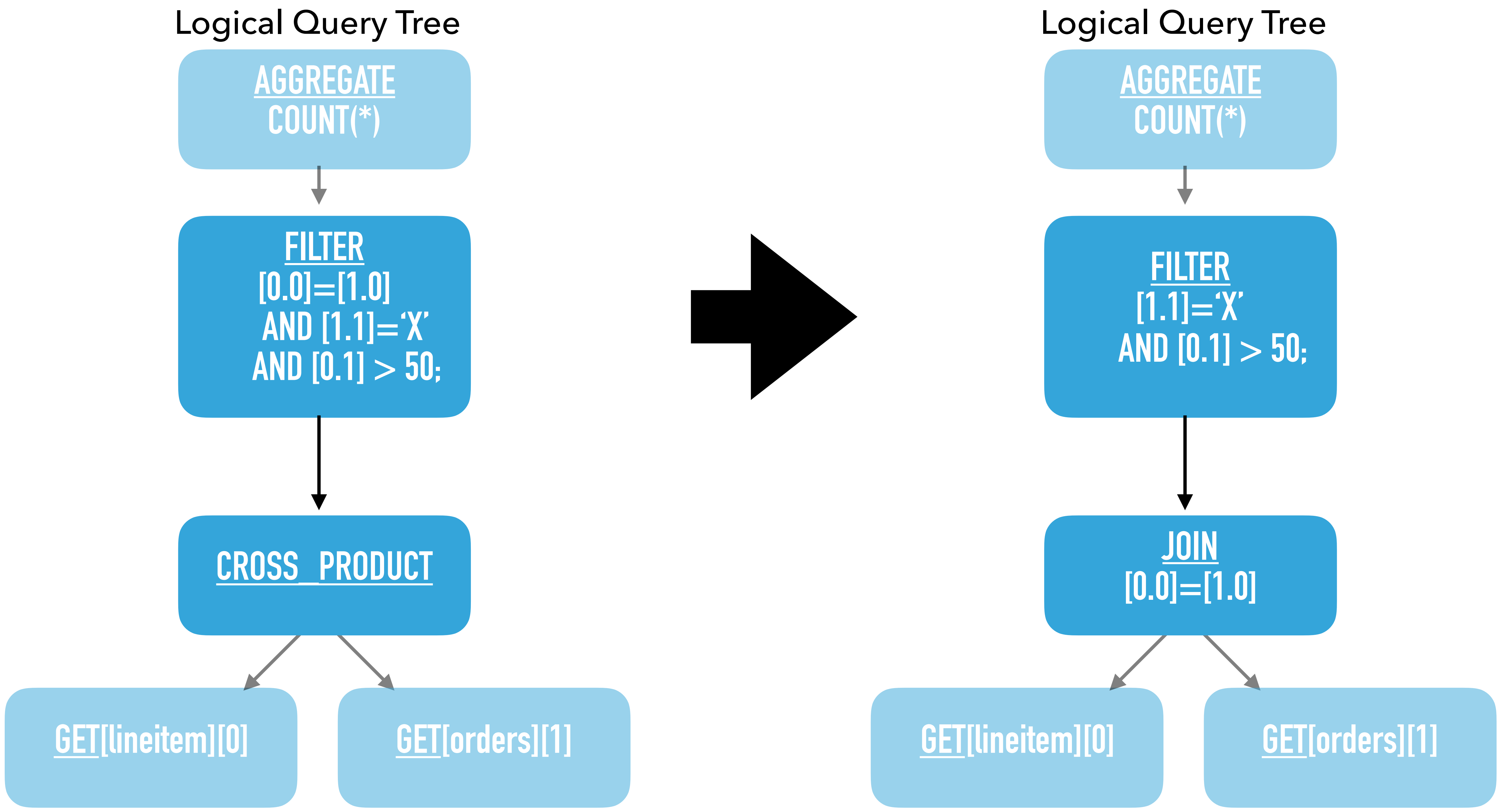
DuckDB



- **Optimizer:** transforms the logical query tree
- Created plan is logically equivalent
  - But (hopefully) faster

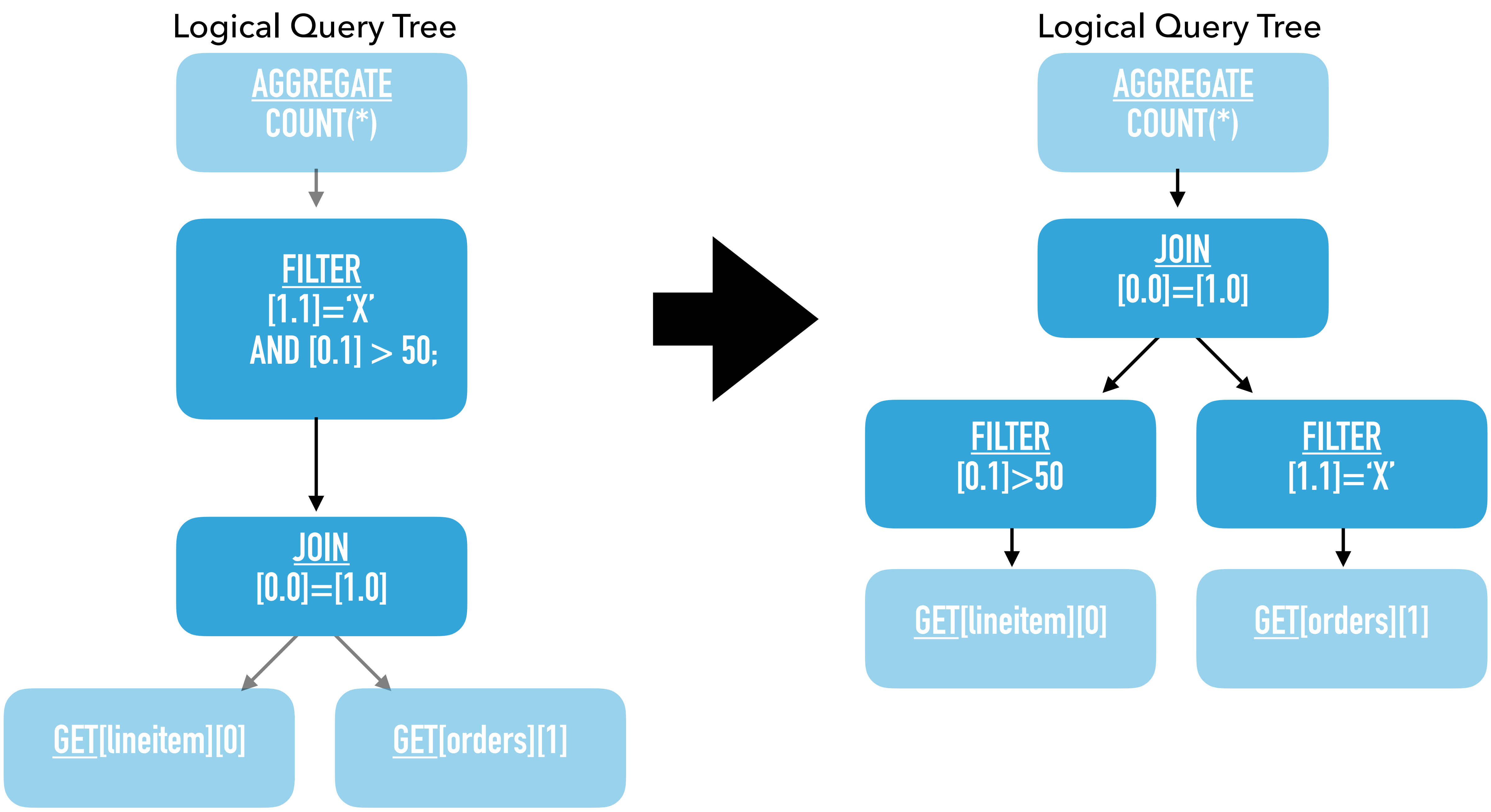
```sql
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

- Pushdown filter into cross product: creates a join

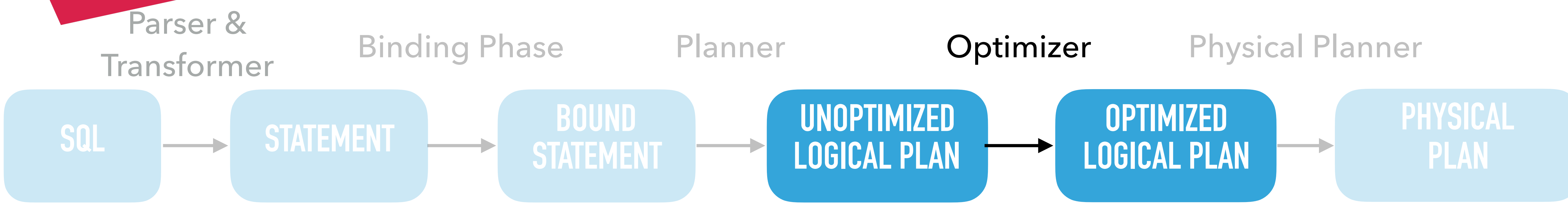


CWI **DuckDB**

- Pushdown filters below the join



DuckDB



- Many possible optimizations possible here
  - Constant folding, CSE, subquery flattening, common subtree elimination, etc…
- For this query only filter pushdown is necessary

```sql
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

DuckDB

Parser & Transformer | Binding Phase | Planner | Optimizer | Physical Planner

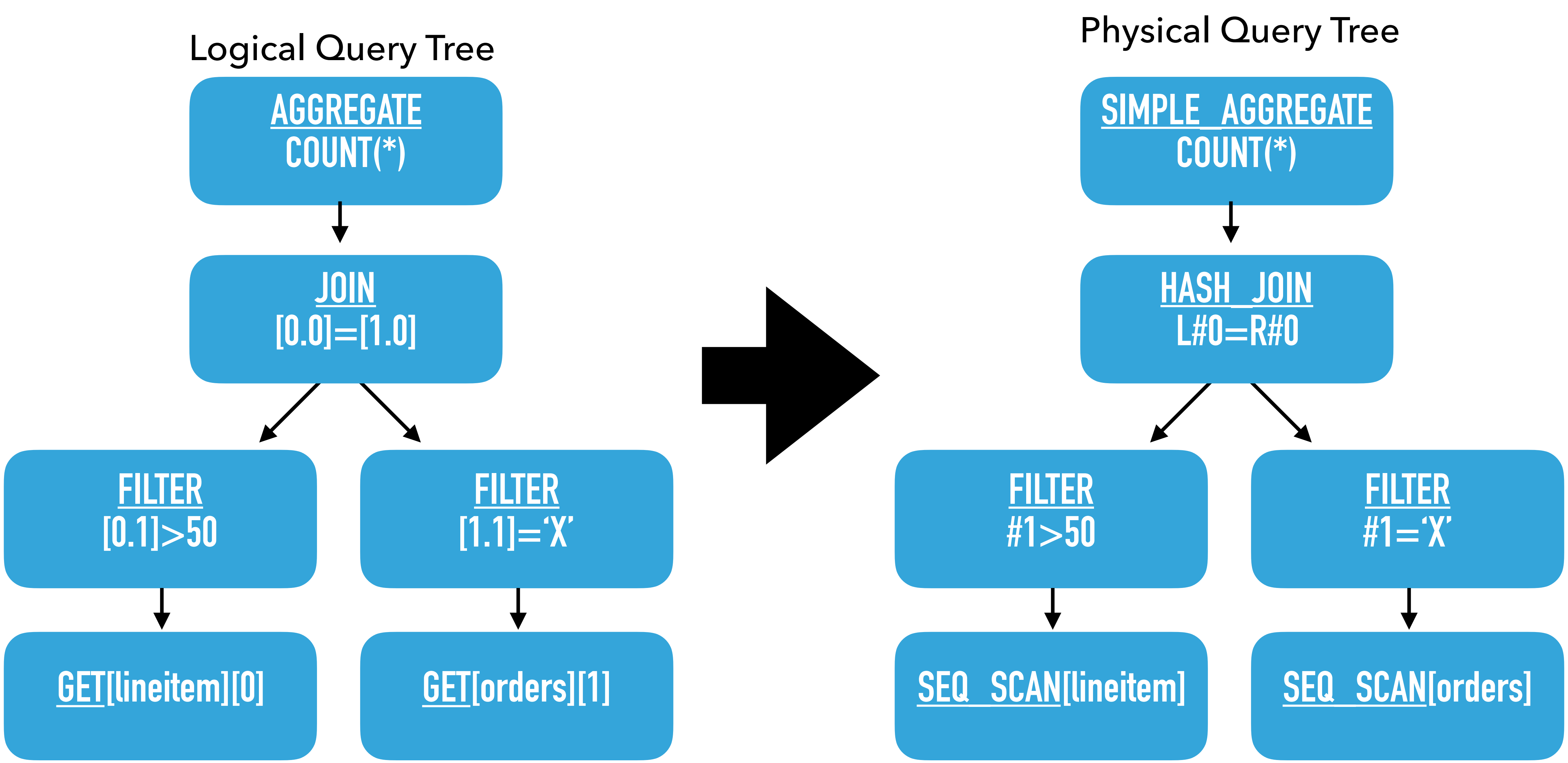
SQL → STATEMENT → BOUND STATEMENT → UNOPTIMIZED LOGICAL PLAN → OPTIMIZED LOGICAL PLAN → PHYSICAL PLAN

- **Physical planner:** converts logical plan into physical (executable) plan
- Makes decision on implementations of operators
  - e.g. use a HashJoin, MergeJoin or NestedLoopJoin

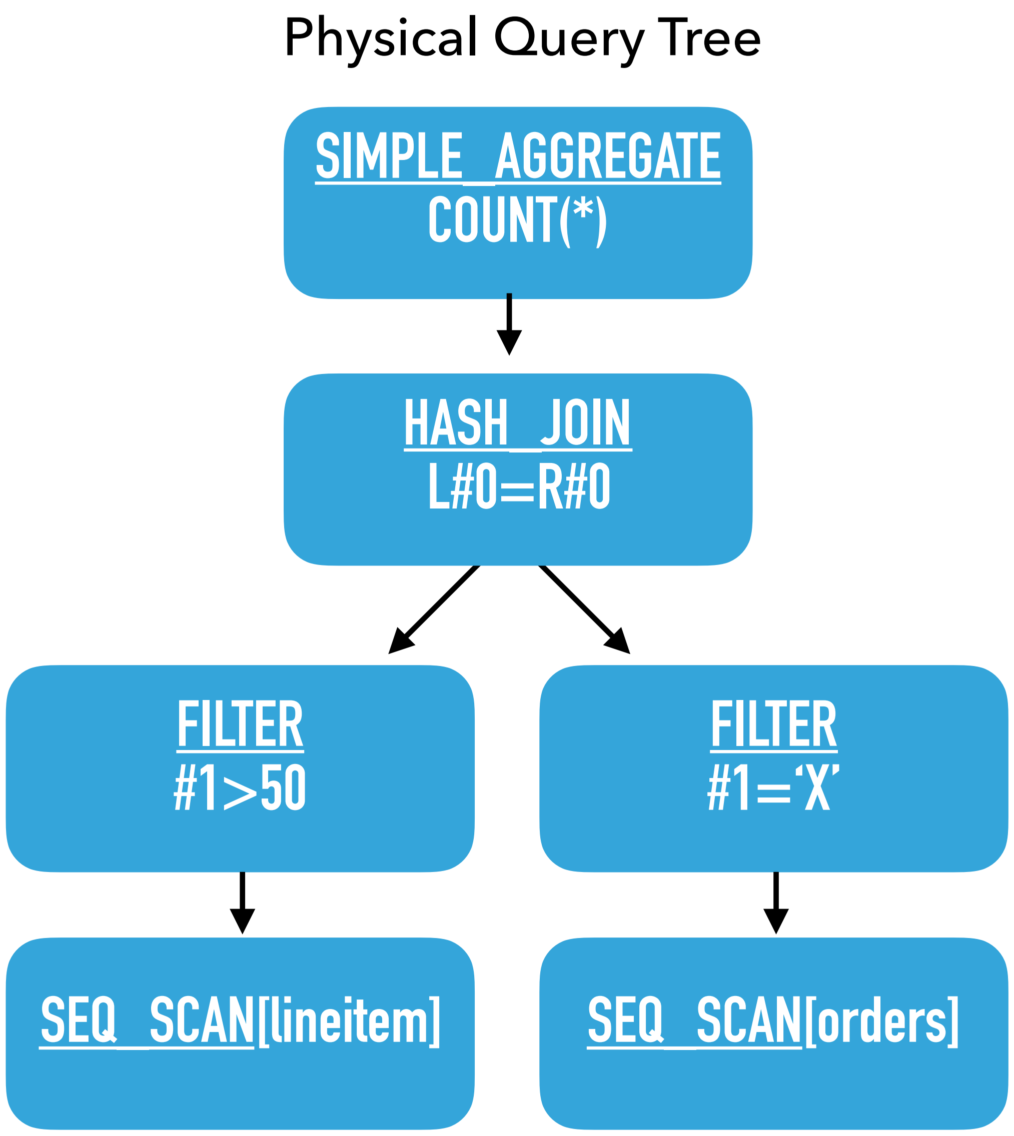
```sql
SELECT COUNT(*)
FROM lineitem, orders
WHERE l_orderkey=o_orderkey
      AND o_orderstatus='X'
      AND l_tax > 50;
```

DuckDB

- **SimpleAggregate:** no groups, no hash required
- **Hash Join:** Most effective for this equality join
- **Sequential Scan:** No index that helps us speed up



- Now we have the final query tree
  - This is what we **execute** to run the query



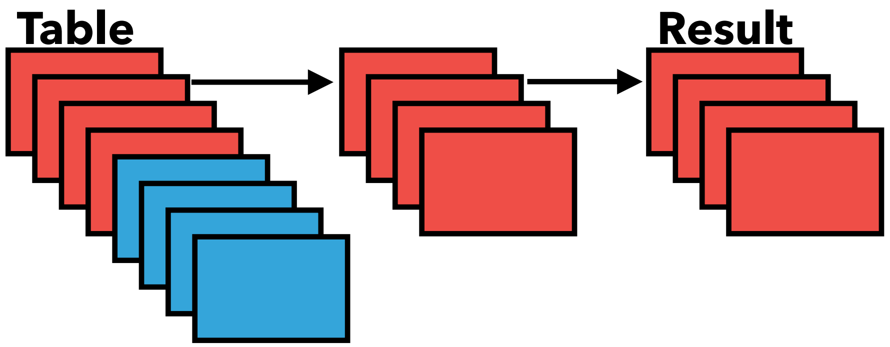
Query Execution

Query Execution

- DuckDB uses a vectorized pull-based model
  - "vector volcano”

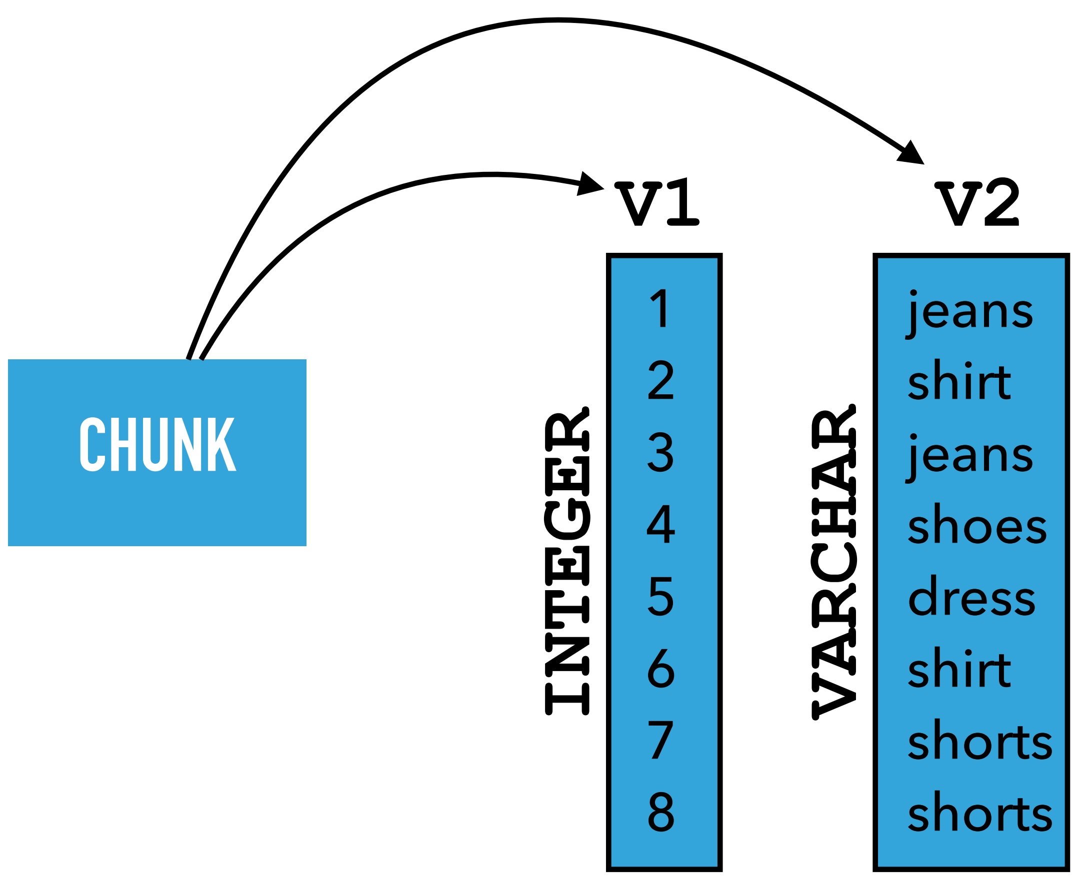
- Query starts by calling `GetChunk` on the root node
- Root node recursively calls `GetChunk` on children
- Scans fetch data from the base tables

Vectorized Processing



Query Execution

- Basic units: `Vector` and `DataChunk`
- `Vector` is a **column-slice**
  - Set of **up to** *1024* values of a single type
- `DataChunk` is a **table-slice** (set of vectors)



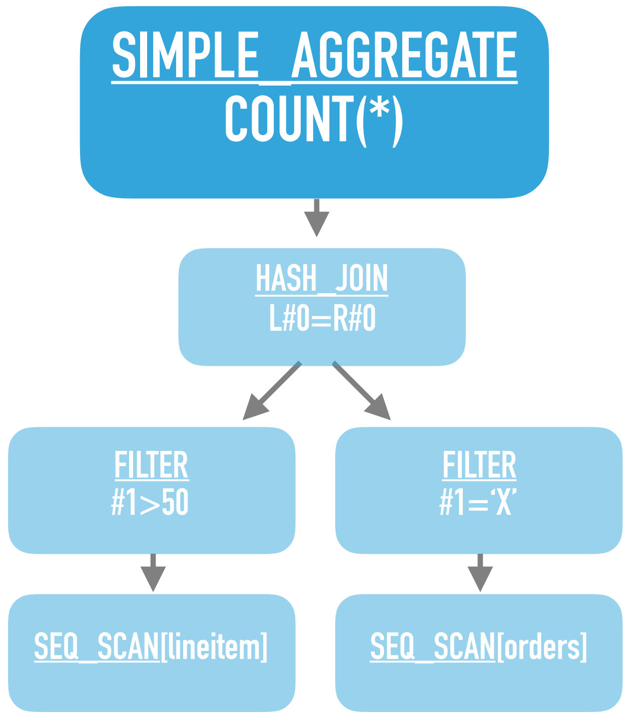
Query Execution

```
class Vector {
public:
    TypeId type;
    index_t count;
    data_ptr_t data;
    sel_t *sel_vector;
    nullmask_t nullmask;
```

```
class DataChunk {
public:
    index_t column_count;
    unique_ptr<Vector[]> data;
```

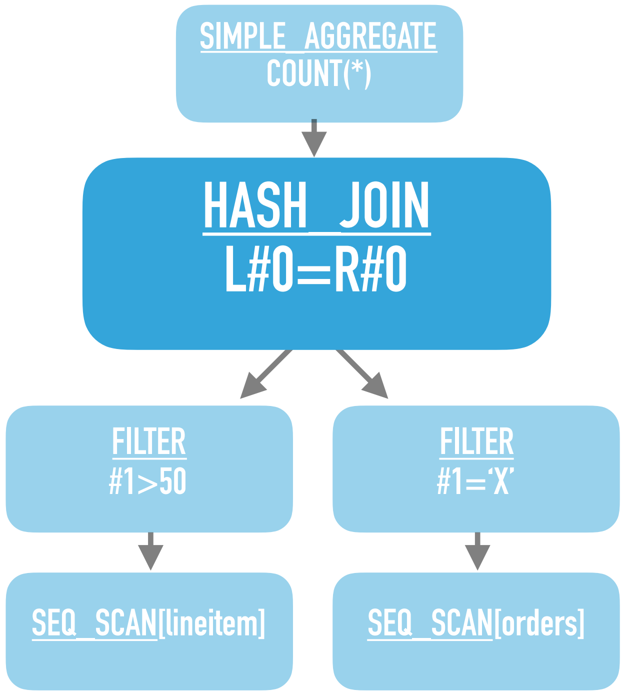
- `nullmask`: bitmap indicating which values are NULL
- `sel_vector`: optional selection vector indicating **which** values to use in the vector

- Start with root node: **SimpleAggregate**
  - Aggregate without groups
- Immediately calls **`GetChunk`** on child



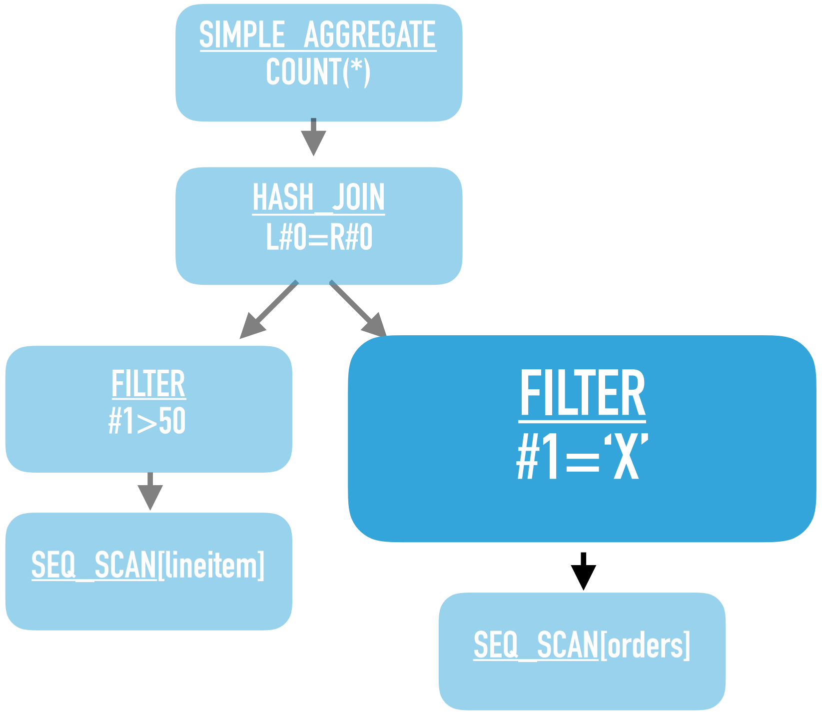
DuckDB

- **Hash Join**
- Start by **building HT**
- Call `GetChunk` on right node



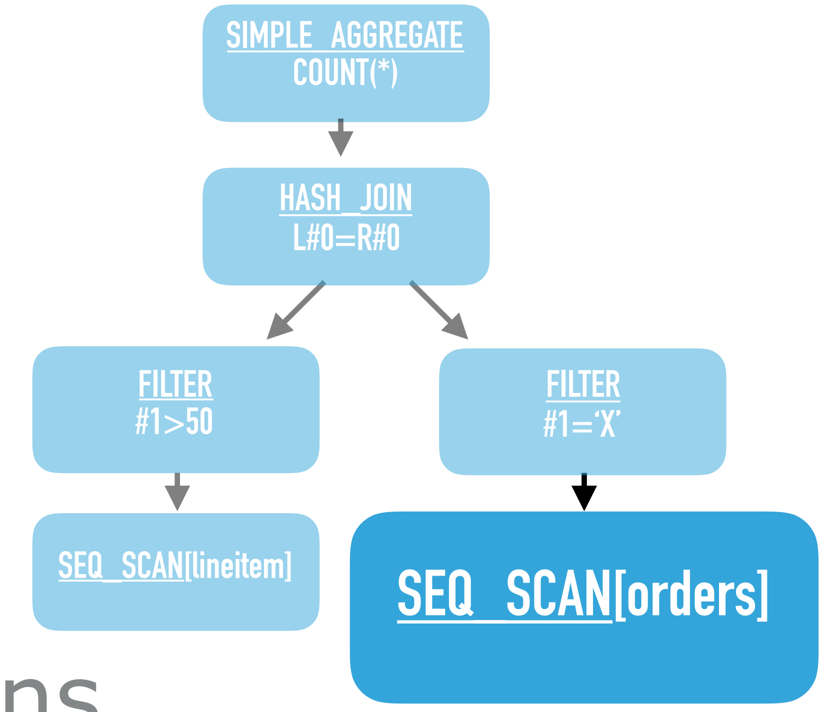
DuckDB

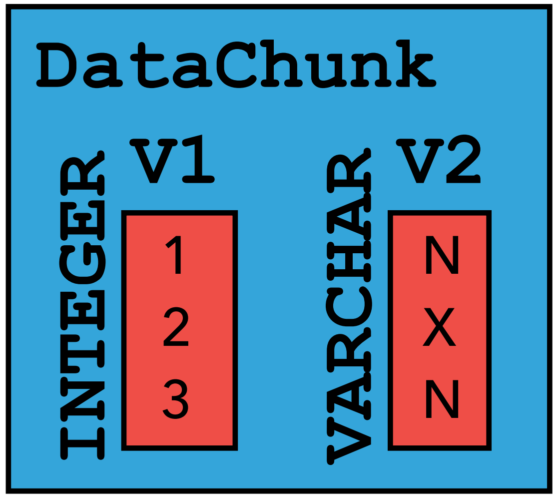
- **Filter**
- Again, pull a chunk from child



DuckDB

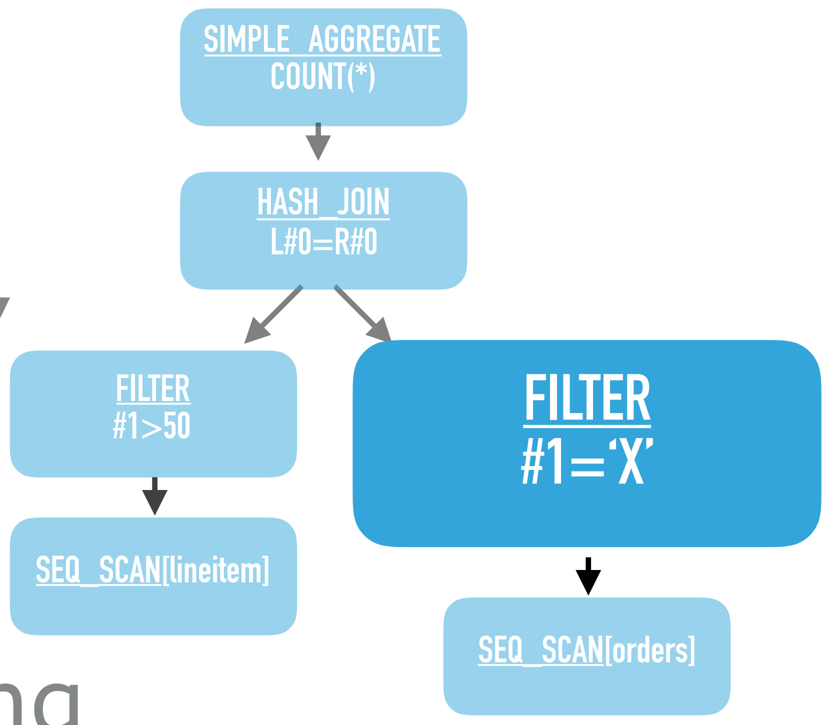
- **Sequential Scan**
- Finally we can start executing
- Scan the base table
- Return a DataChunk with two columns
  - `o_orderkey` and `o_orderstatus`

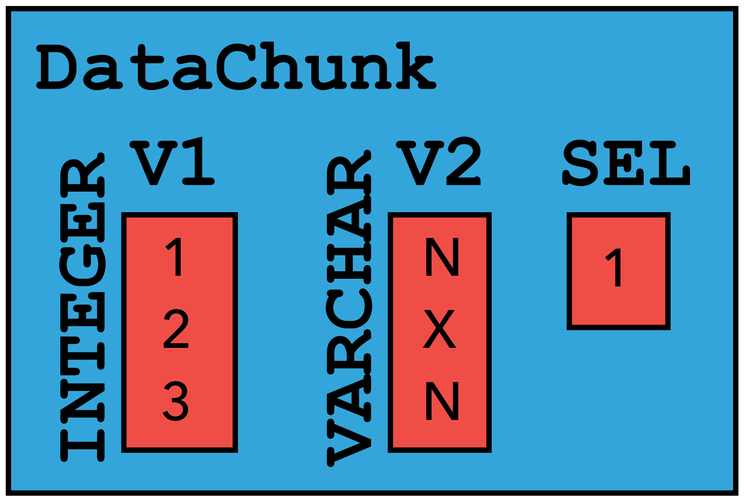




DuckDB

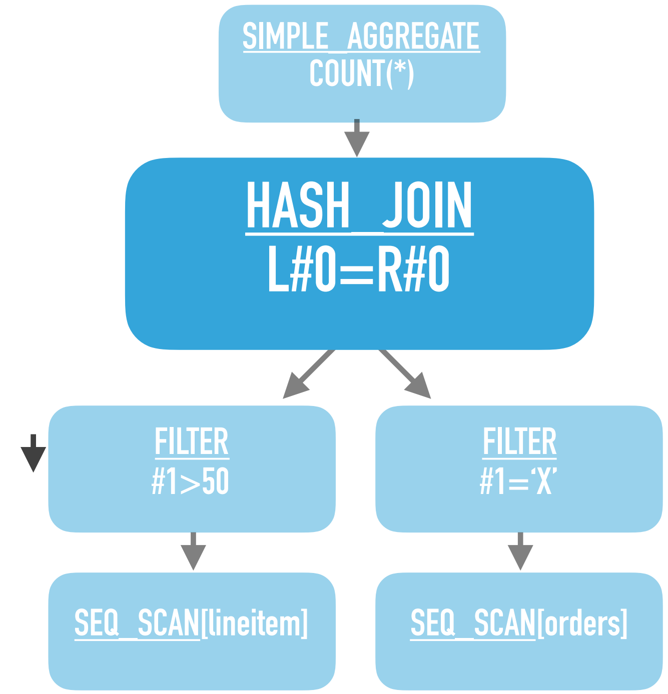
- **Filter**
- Now we can perform the filter #1='X'
  - Only the second tuple passes
- **Selection vector** pointing to surviving tuple is created
- Note that no data is copied or changed

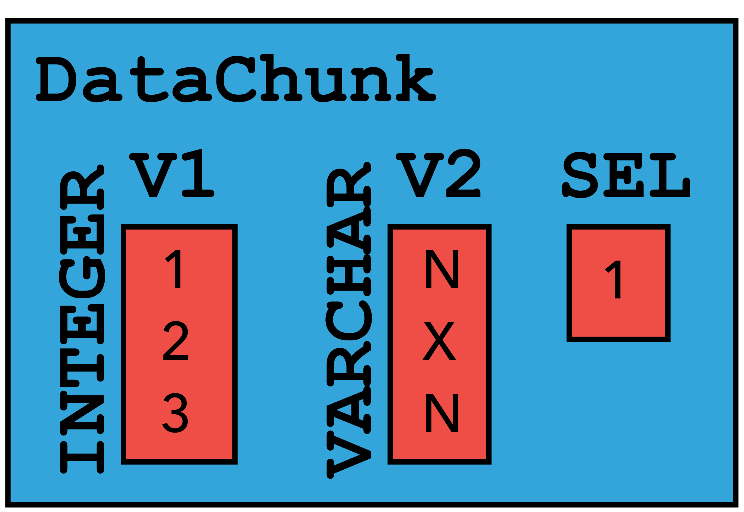


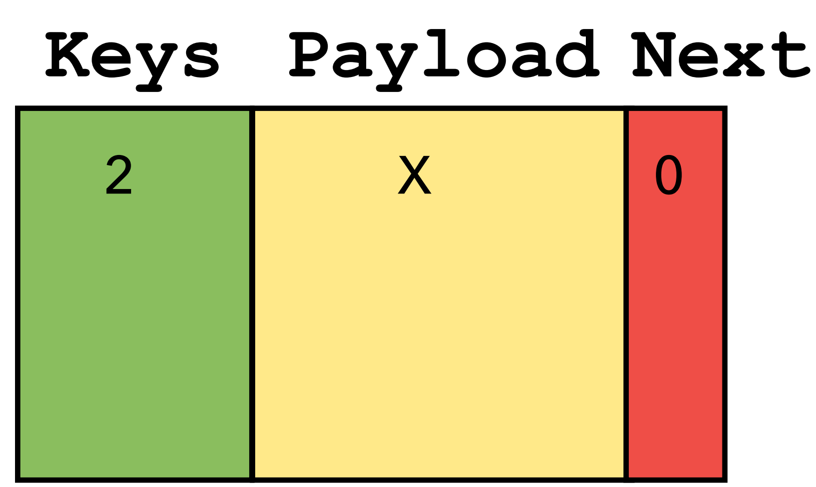


DuckDB

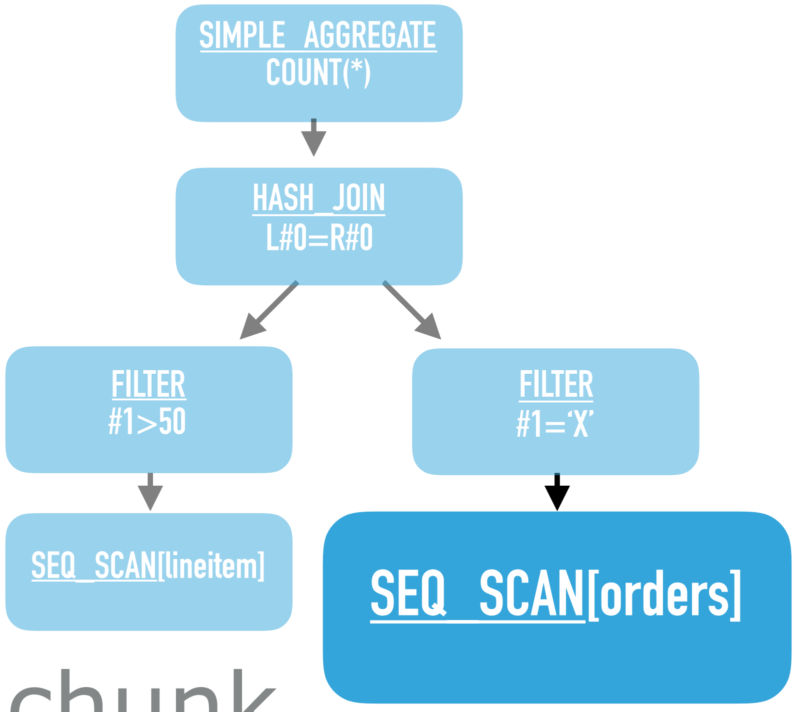
- **Hash Join**
- Now we have our first input chunk
- We input it into the HT
- Now we fetch another chunk from RHS

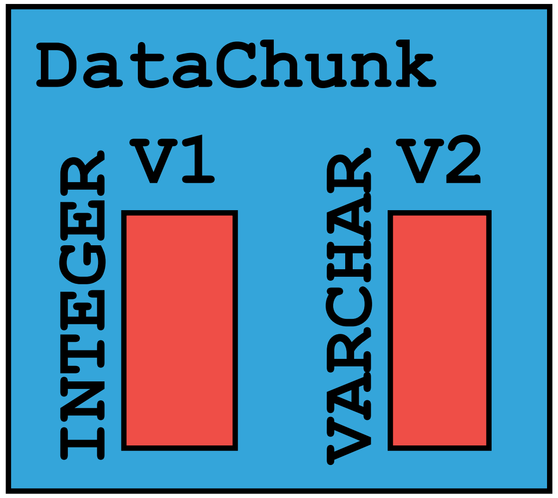




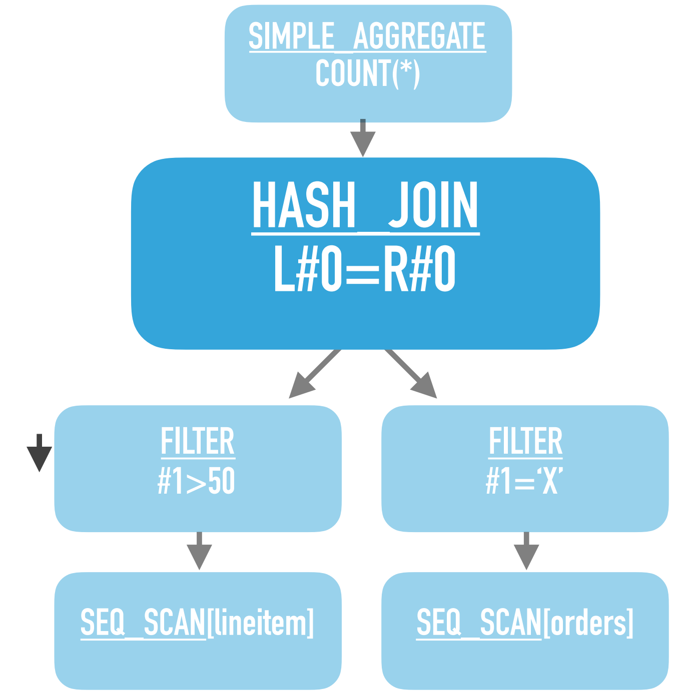


- **Sequential Scan**
- The filter again calls **`GetChunk`**
- Scan base table again:
  - The scan is finished, return empty chunk

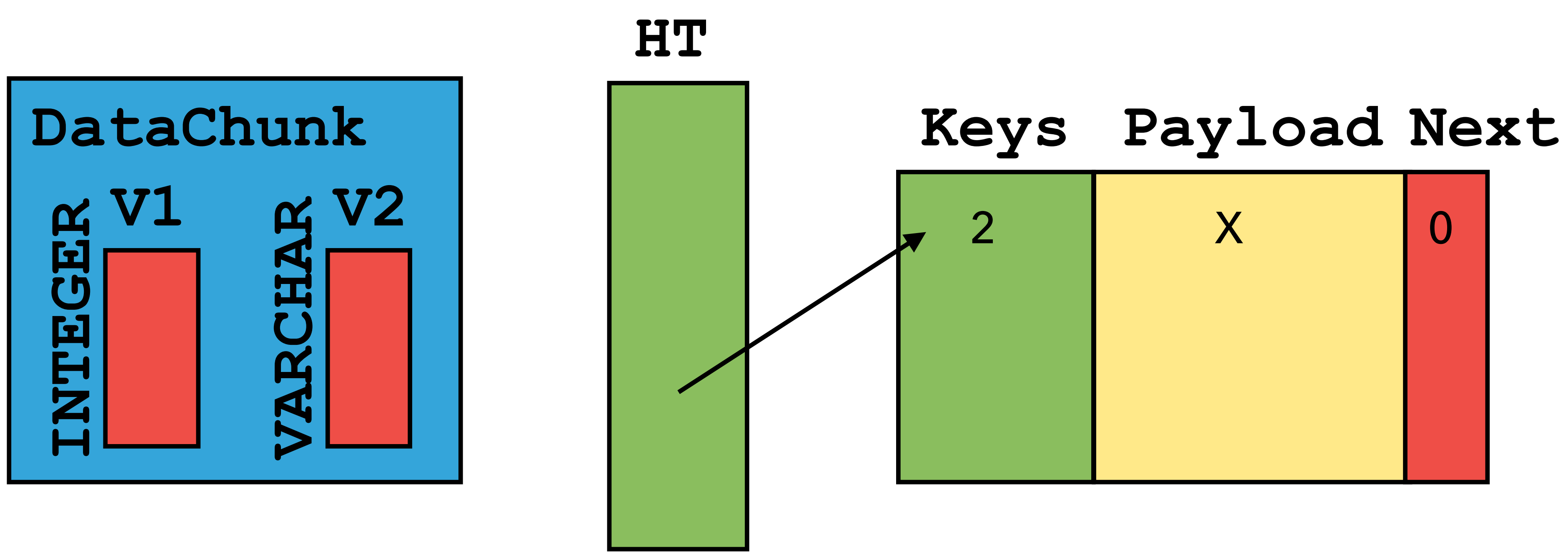




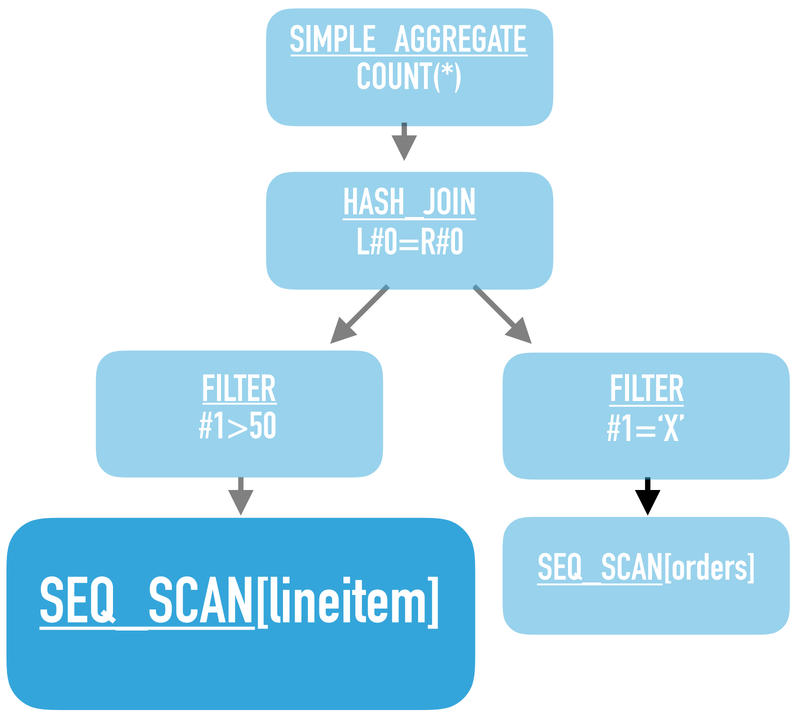
DuckDB

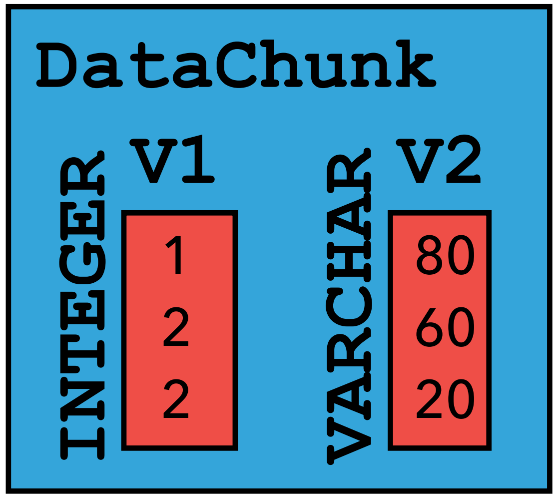


- **Hash Join**
- HT receives second input chunk
  - But it is empty!
- The RHS is exhausted
- Finish building HT and call `GetChunk` on LHS



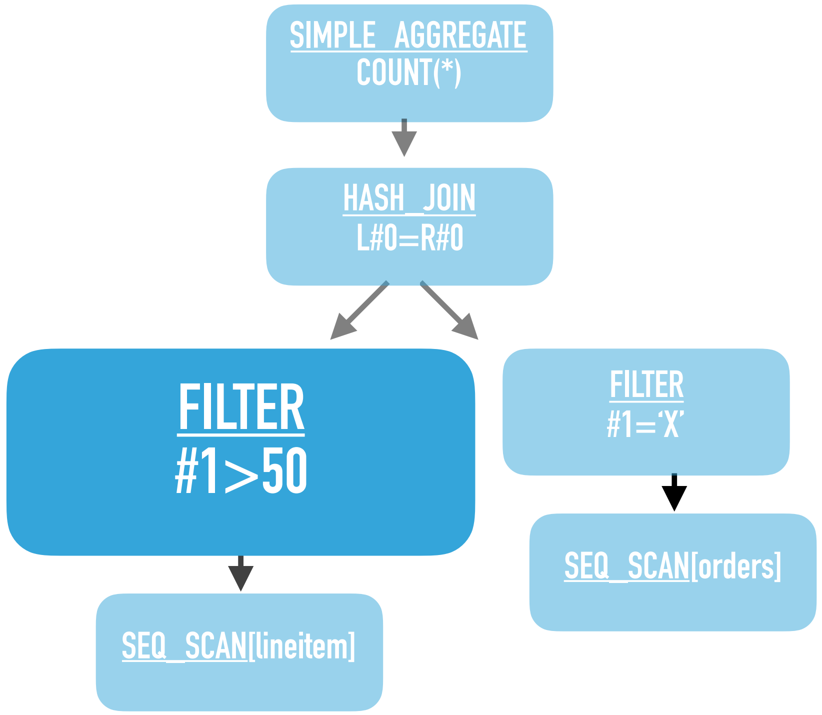
- **Sequential Scan**
- We arrive at scan on lineitem
- DataChunk with two columns
  - `l_orderkey` and `l_tax`

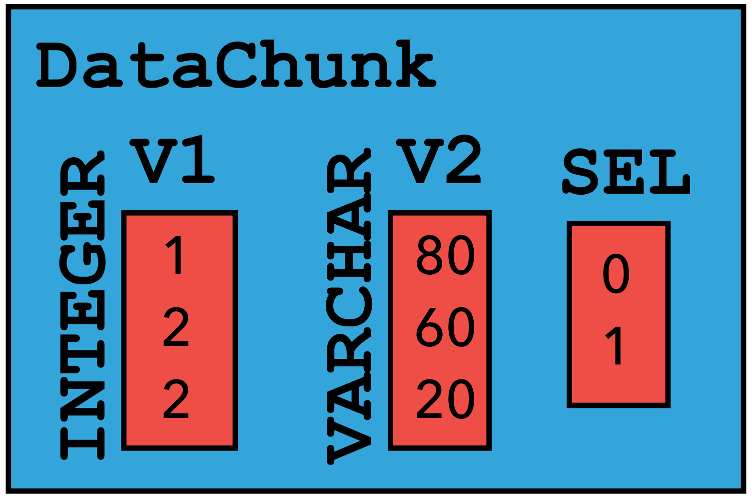




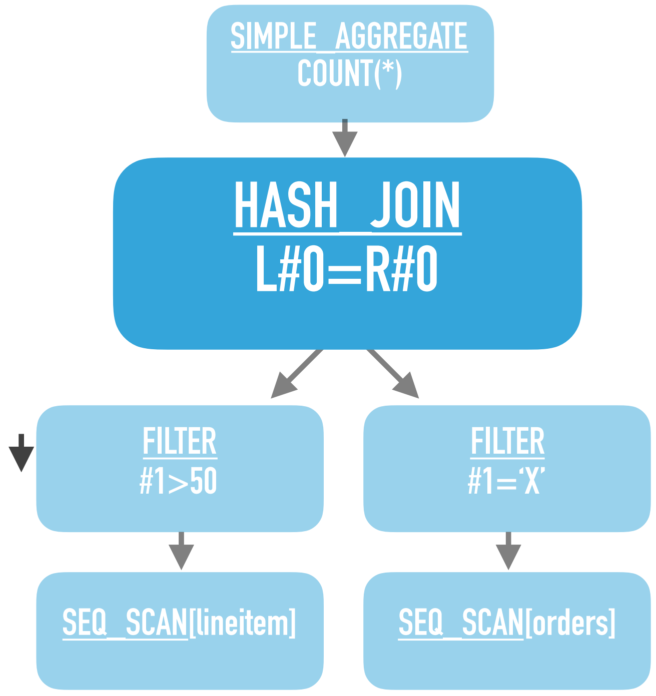
DuckDB

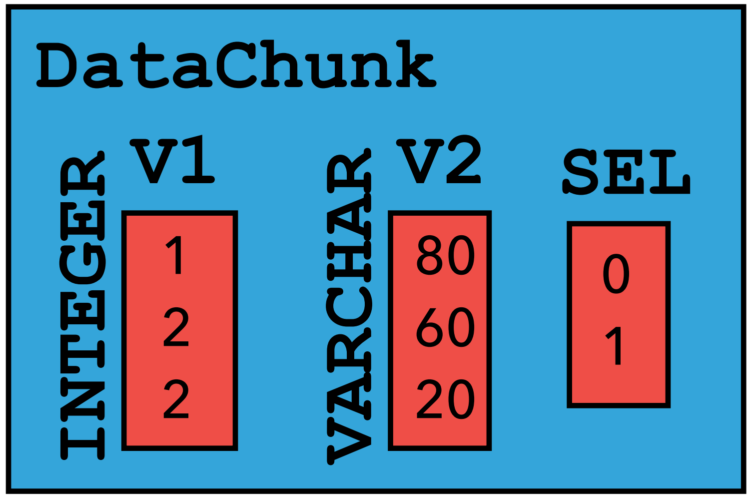
- **Filter**
- Performs the filter **#1>50**
- Again, add a selection vector

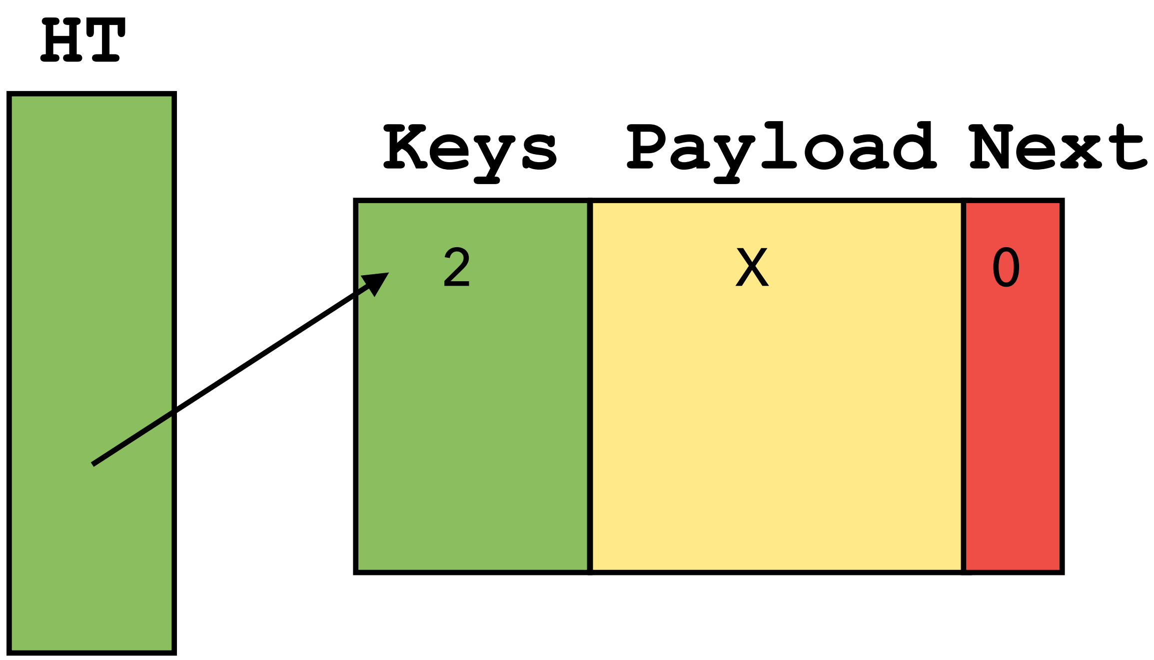




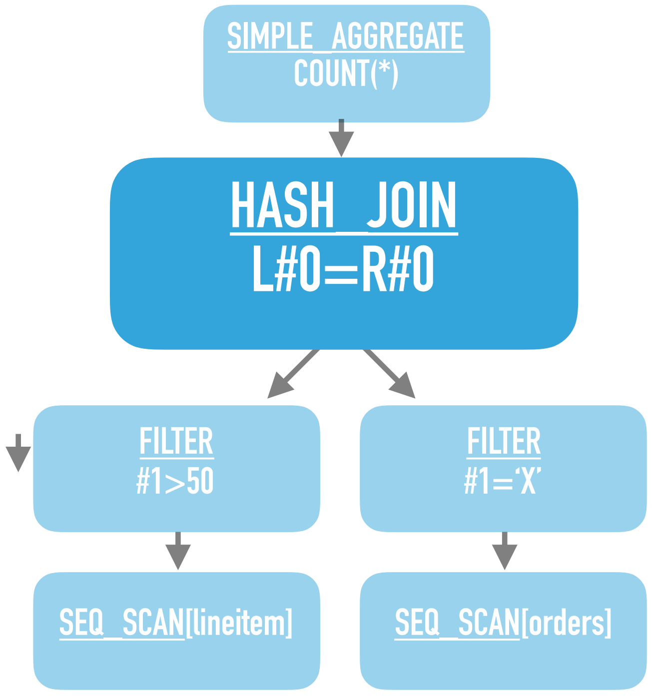
- **Hash Join**
- Now it is time to probe the HT
- We compute the hash for each tuple
- Then lookup in the HT

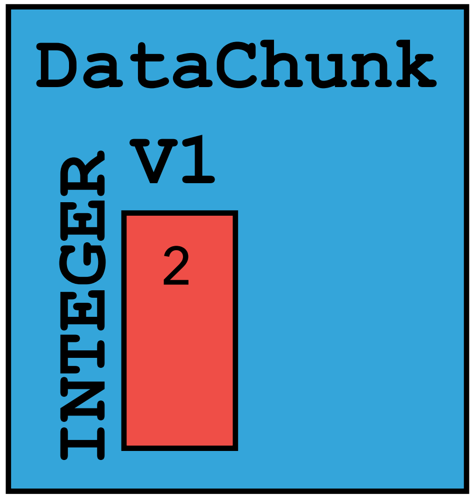






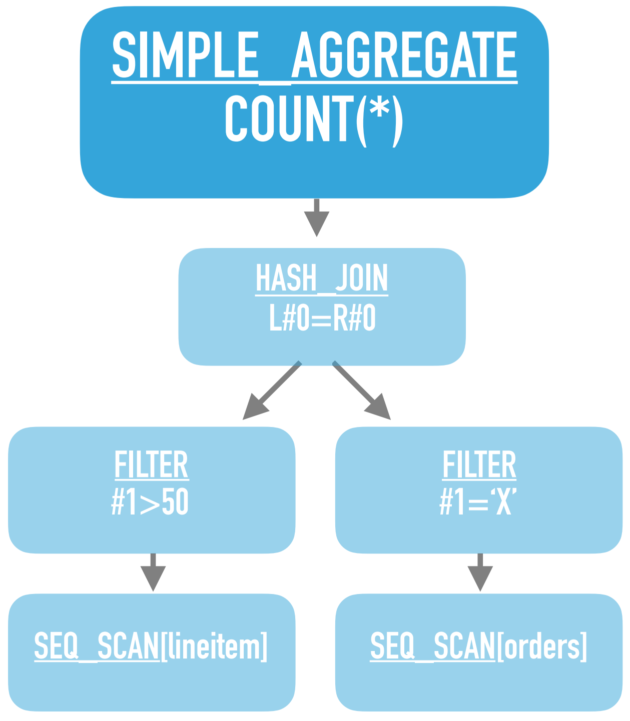
- **Hash Join**
- We get one hit on our join!
- The hash join now produces the result
- We return this to the aggregate

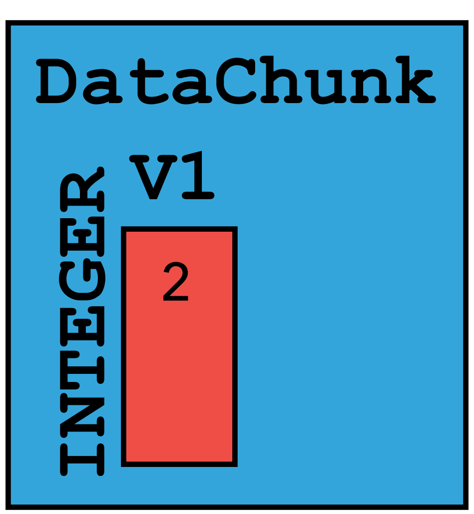


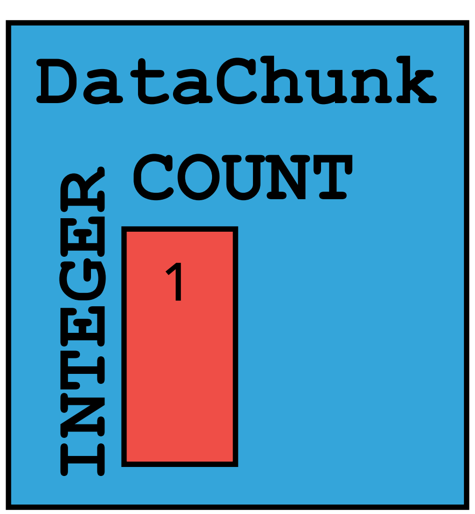


DuckDB

- The aggregate takes our input chunk
- Updates the aggregate
- Then fetches from the child again

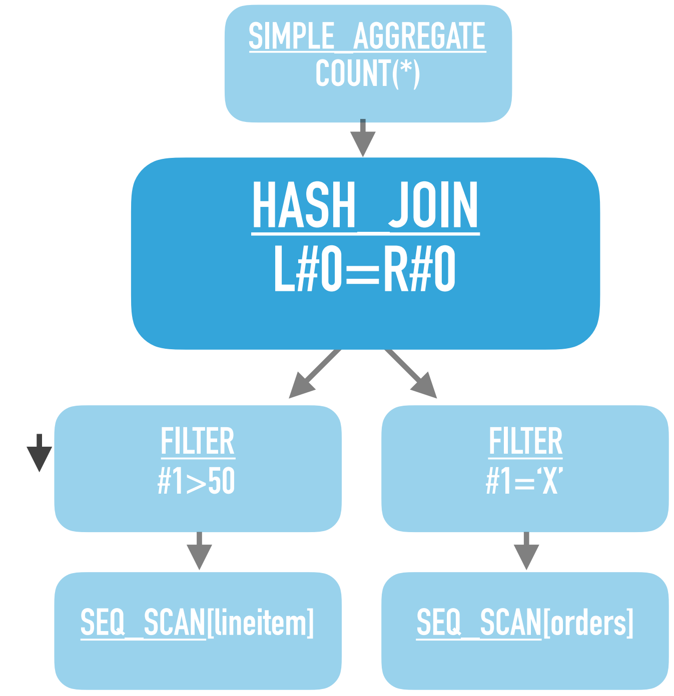


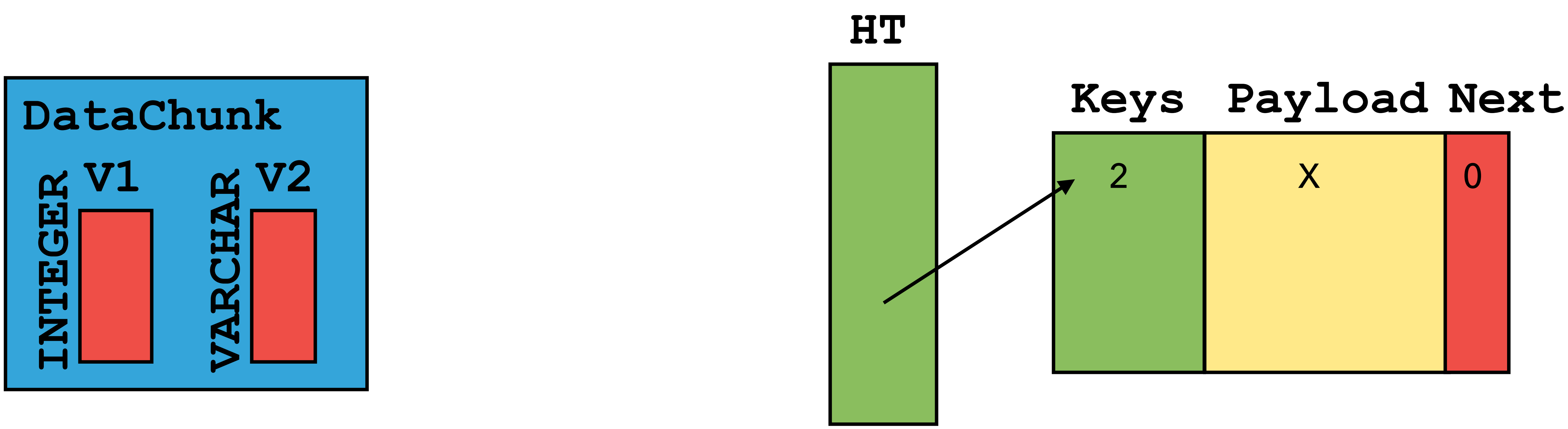




DuckDB

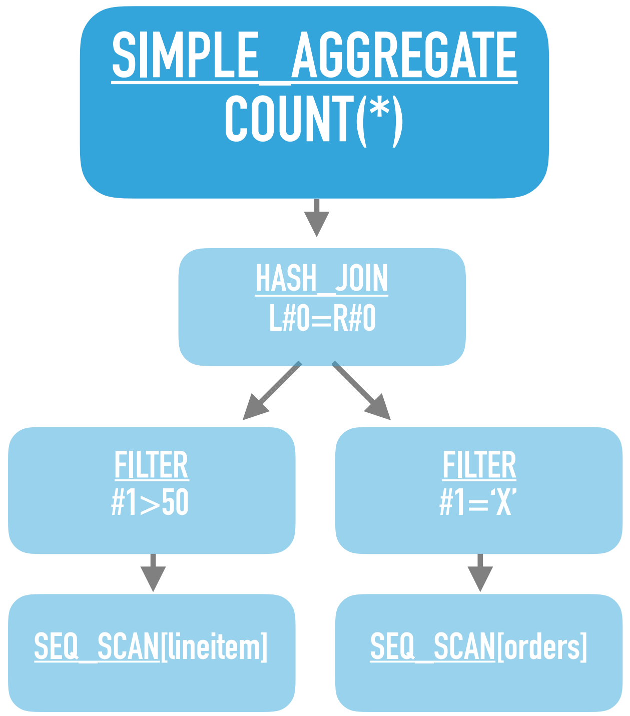
- We go back to the hash join
- Fetch from probe side again
- This time, input chunk is empty
- Now the hash join is entirely finished!

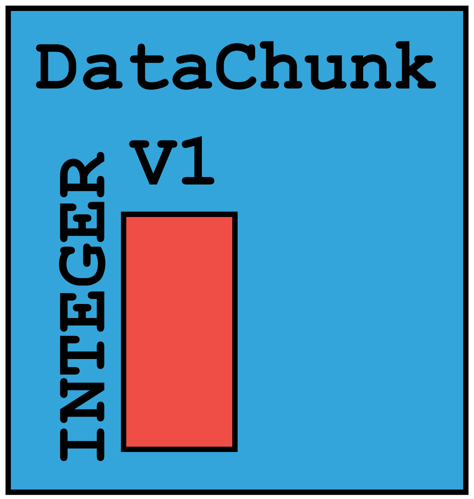


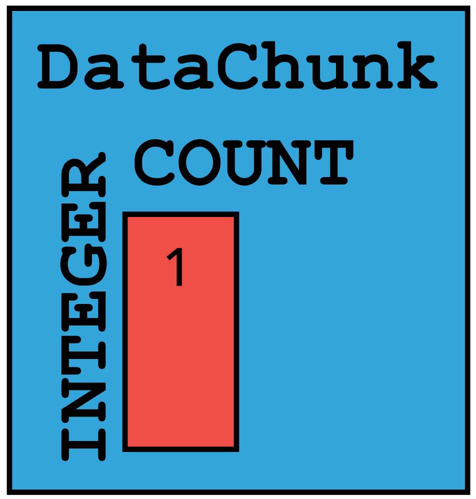


DuckDB

- Aggregate gets an empty chunk
- Returns the final result of our query



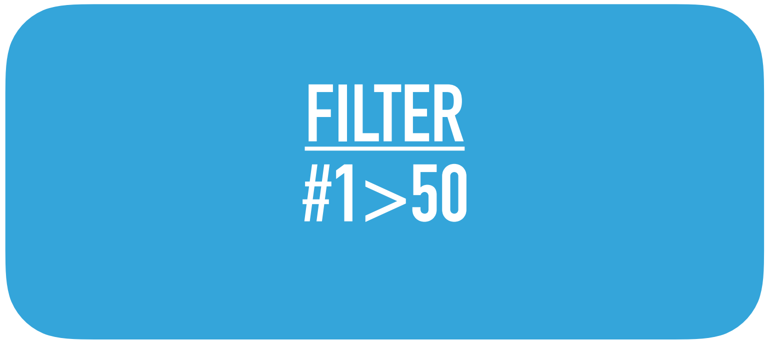


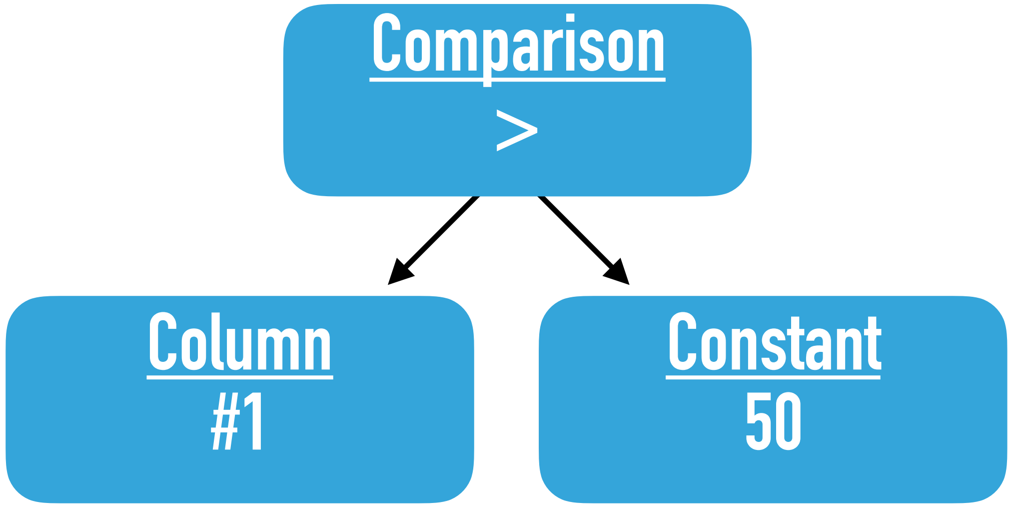


Expression Execution

Expression Execution

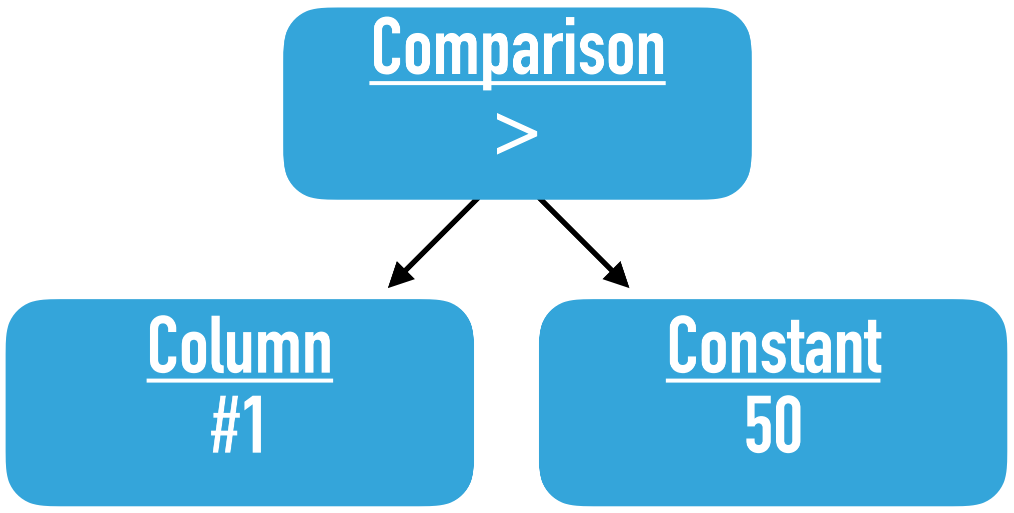
- **Expressions** exist within the query tree nodes
  - Filter has a set of **filter predicates**
  - Projection has **projection list**
- Represented as **expression tree**



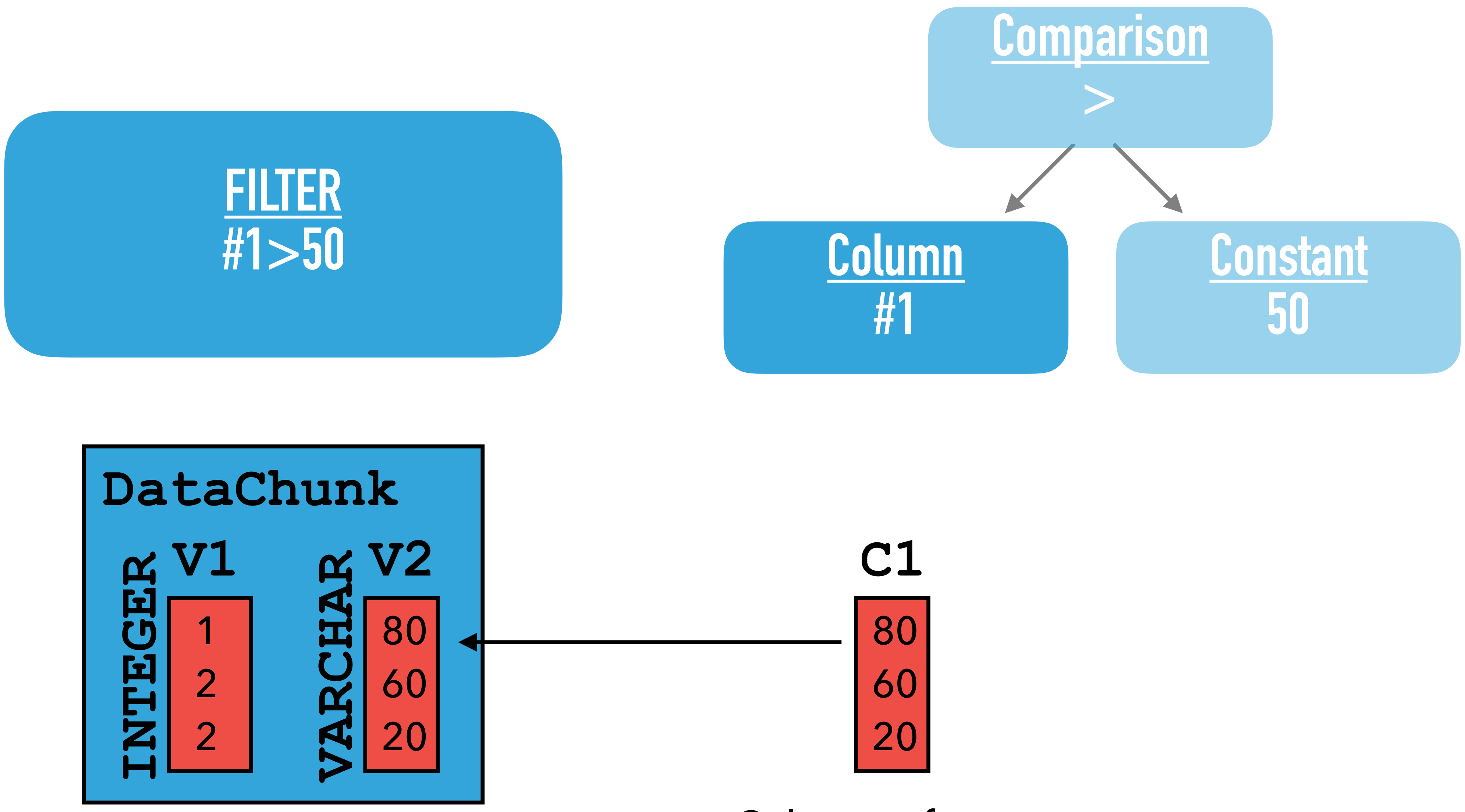


Expression Execution

- **ExpressionExecutor** runs the expressions
- This occurs as part of the execution of the node
- Expressions are executed in vectorized fashion

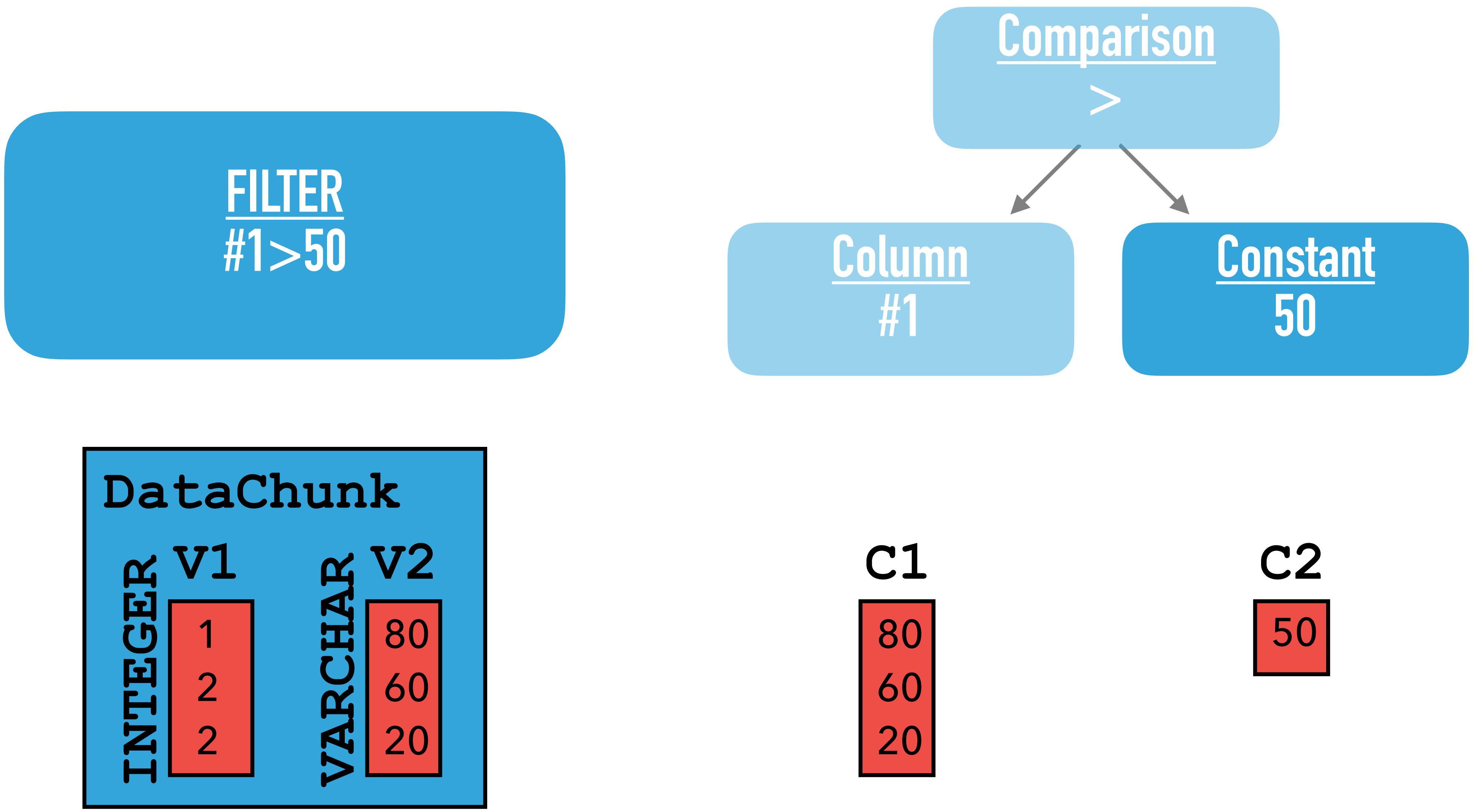


Expression Execution



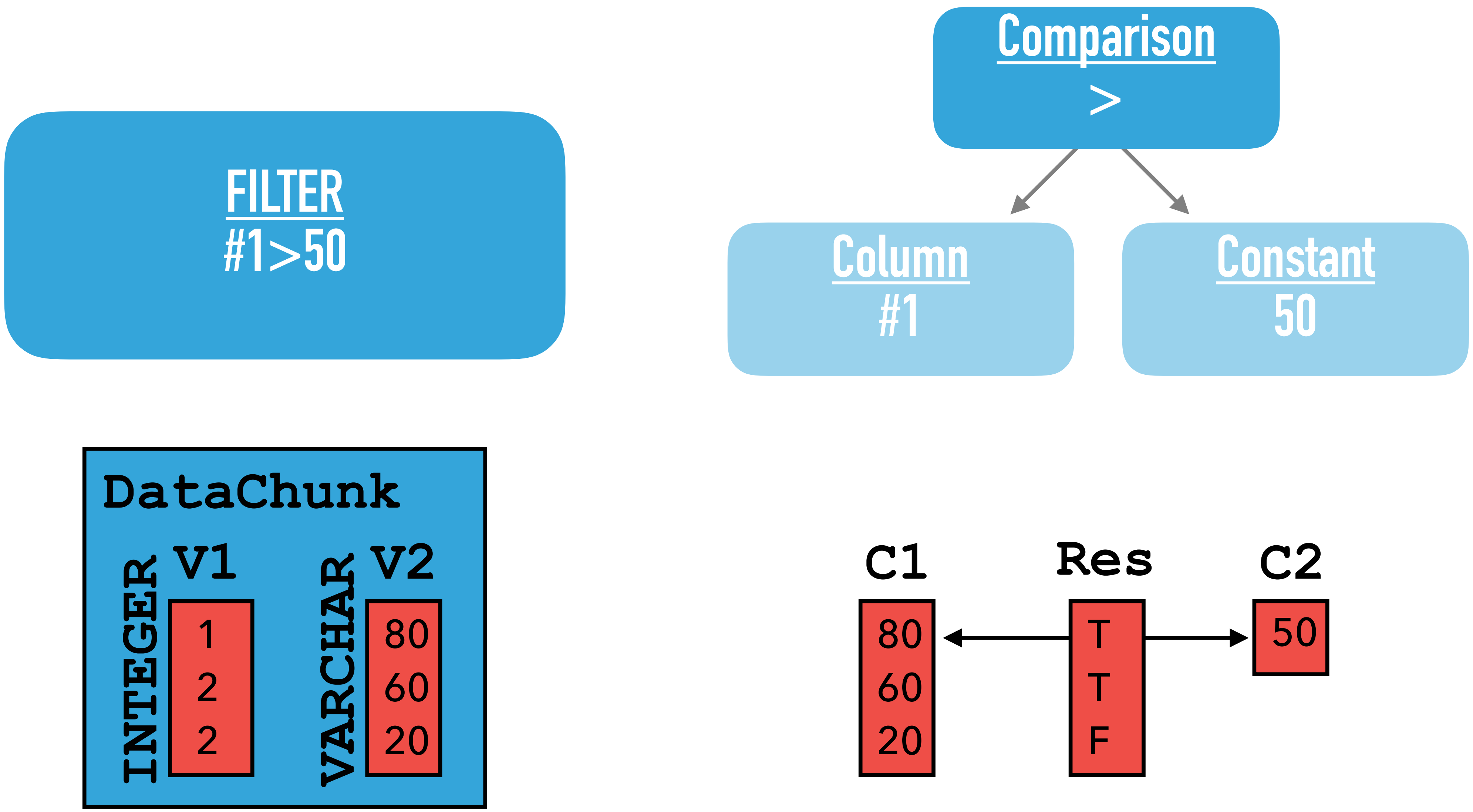
Column reference
#1 fetches second
column from input

Expression Execution



Constant is a single value

Expression Execution



Comparison runs and returns matching tuples

Hands On

Hands On

- **Assignment**: Implement a function in DuckDB
- Open issues for functions from other systems:
- https://github.com/cwida/duckdb/issues/193
- Implement one of those
  - For those that are successful, submit a PR!

Set Up & Testing

Set up

- **Set up:**
- 1. Download the source code
  - `git clone` https://github.com/cwida/duckdb
- 2. Compile the source code
  - First download CMake if you don't have it
  - **Linux/OSX:** `make debug`
  - **Windows:** Use CMake to generate a Visual Studio project, then build it from Visual Studio

Set up

- Tests are in the `test` directory
  - We use the Catch framework for tests
- Tests look like this:

```
TEST_CASE("Test scalar queries", "[scalarquery]") {
    unique_ptr<QueryResult> result;
    DuckDB db(nullptr);
    Connection con(db);
    con.EnableQueryVerification();

    result = con.Query("SELECT 42");
    REQUIRE(CHECK_COLUMN(result, 0, {42}));

    result = con.Query("SELECT 42 + 1");
    REQUIRE(CHECK_COLUMN(result, 0, {43}));

    result = con.Query("SELECT 2 * (42 + 1), 35 - 2");
    REQUIRE(CHECK_COLUMN(result, 0, {86}));
    REQUIRE(CHECK_COLUMN(result, 1, {33}));
```

Create in-memory database

Run queries
& verify result

Set up

- Tests can be run as follows:
- **Linux/OSX:**
- `build/debug/test/unittest “Test scalar queries”`
- **Windows**
- Run `unittest` project
- Command line parameter: `“Test scalar queries”`

```
TEST_CASE("Test scalar queries", "[scalarquery]") {
	unique_ptr<QueryResult> result;
	DuckDB db(nullptr);
	Connection con(db);
	con.EnableQueryVerification();

	result = con.Query("SELECT 42");
```

Function Definition

Function Definition

- Each function has different **overloads**

Addition

+

- e.g. addition operator:
  - +(SMALLINT,SMALLINT)
  - +(INTEGER,INTEGER)
  - +(BIGINT,BIGINT)
  - …
- **Binder** chooses which version to use

Function Definition

- Set of permitted **implicit casts**

Addition
+

- TINYINT → SMALLINT, INTEGER, BIGINT, FLOAT, DOUBLE
- SMALLINT → INTEGER, BIGINT, FLOAT, DOUBLE
- INTEGER → BIGINT, FLOAT, DOUBLE
- BIGINT → FLOAT, DOUBLE
- FLOAT → DOUBLE

Function Definition

Addition

+

- Binder prefers to cast as little as possible
- e.g. TINYINT + INTEGER has multiple eligible options
- INTEGER + INTEGER will be chosen
  - Requires only one implicit cast
- Other options require two casts:
  - BIGINT + BIGINT, FLOAT+FLOAT, DOUBLE + DOUBLE

Function Definition

- The same binding rules apply to **functions**
  - **`substring(string, start, length)`**
  - Three parameters: **`VARCHAR, INTEGER, INTEGER`**
- Binder will automatically insert CAST if required
  - e.g. TINYINT → INTEGER
- In the code for **substring** we only need to implement the case with parameters `VARCHAR, INTEGER, INTEGER`

Expression Execution

- Code: how to add a function definition

```
set.AddFunction(ScalarFunction(
    "substring",            // name of function
    { SQLType::VARCHAR,     // argument list
      SQLType::INTEGER,
      SQLType::INTEGER },
    SQLType::VARCHAR,       // return type
    substring_function)); // pointer to function implementation
```

- Function code is implemented in `substring_function`

Creating a Simple Function

Creating a Simple Function

- Create a simple function:
  - `add_one(INTEGER) -> INTEGER`
- This function adds one to its integer input
- Returns the result

Creating a Simple Function

- **Step one: Create tests**
- Navigate to `test/sql/function`
- Create a new file: `test_add_one.cpp`
- Add it to `CMakeLists.txt` in that folder

Creating a Simple Function

- Step one: Create tests

```
TEST_CASE("Te Loading... function", "[function]") {
    unique_ptr<QueryResult> result;
    DuckDB db(nullptr);
    Connection con(db);
    con.EnableQueryVerification();

    REQUIRE_NO_FAIL(con.Query("CREATE TABLE integers(i INTEGER)"
    REQUIRE_NO_FAIL(con.Query("INSERT INTO integers VALUES "
                              "(1), (2), (3), (NULL)"));

    result = con.Query("SELECT add_one(1)");
    REQUIRE(CHECK_COLUMN(result, 0, {2}));
    result = con.Query("SELECT add_one(NULL)");
    REQUIRE(CHECK_COLUMN(result, 0, {Value()}));
    result = con.Query("SELECT add_one(i) FROM integers"
                       " ORDER BY 1");
    REQUIRE(CHECK_COLUMN(result, 0, {Value(), 2, 3, 4}));
    result = con.Query("SELECT add_one(i) FROM integers"
                       " WHERE i>1 ORDER BY 1");
    REQUIRE(CHECK_COLUMN(result, 0, {3, 4}));
}
```

Scalar tests

Table + selection vector tests

Creating a Simple Function

- Step one: Create tests

```
> build/debug/test/unittest "Test add one function"
Query failed with message: Catalog: Function with name add_one does not exist!

~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
unittest is a Catch v2.4.0 host application.
Run with -? for options

-------------------------------------------------------------------------------
Test add one function
-------------------------------------------------------------------------------
/Users/myth/Programs/duckdb/test/sql/function/test_add_one.cpp:7
...............................................................................

/Users/myth/Programs/duckdb/test/sql/function/test_add_one.cpp:18: FAILED:
  REQUIRE( CHECK_COLUMN(result, 0, {2}) )
with expansion:
  false

===============================================================================
test cases: 1 | 1 failed
assertions: 3 | 2 passed | 1 failed
```

Creating a Simple Function

- **Step two: Create the function**
- Navigate to `src/function/scalar`
- All function implementations are here
- In `math` directory, create new file: `add_one.cpp`
  - And add it to the CMakeLists.txt

Creating a Simple Function

- **Step two: Create the function**

- Add code to register function:

```
void AddOne::RegisterFunction(BuiltinFunctions &set) {
	set.AddFunction(ScalarFunction("add_one",
	    { SQLType::INTEGER },
		SQLType::INTEGER,
		add_one_function));
}
```

Creating a Simple Function

- **Step two: Create the function**

- Now add actual function code:

```
static void add_one_function(
        ExpressionExecutor &exec,
        Vector inputs[], index_t input_count,
        BoundFunctionExpression &expr, Vector &result) {
    result.Initialize(TypeId::INTEGER);
    VectorOperations::UnaryExec<int32_t, int32_t>(
        inputs[0], result, [&](int32_t input) {
        return input + 1;
    });
}
```

Initialize result

Loop over input & compute result

Creating a Simple Function

- **Step two: Create the function**
- Finally add some more bookkeeping code:
- `include/function/scalar/math_functions.hpp`

```
struct AddOne {
    static void RegisterFunction(BuiltinFunctions &set);
};
```

- `function/scalar/math_functions.cpp`

```
void BuiltinFunctions::RegisterMathFunctions() {
    Register<AddOne>();
```

Creating a Simple Function

- **Step two: Create the function**
- Now run the tests

```
> build/debug/test/unittest "Test add one function"
===============================================================================
All tests passed (6 assertions in 1 test case)
```

- Everything passes!

Creating a Simple Function

- Time to implement your own function
- **Advice**: Start with the `add_one` function
- Once that works, move on to different functions

Creating a Simple Function

- **Suggestions:**
- `RTRIM(VARCHAR) -> VARCHAR` [MySQL]
  - Remove spaces on right side of string
- `REVERSE(VARCHAR) -> VARCHAR` [MySQL]
  - Reverse characters of a string
- `REPEAT(VARCHAR, INTEGER) -> VARCHAR` [MySQL]
  - Repeat the specified string a number of times
- `INSTR(VARCHAR, VARCHAR) -> BOOL` [SQLite]
  - Returns true if second string is part of first string

Creating a Simple Function

- **Slides are online**
- https://github.com/pdet/duckdb-tutorial

- Feel free to ask any questions!