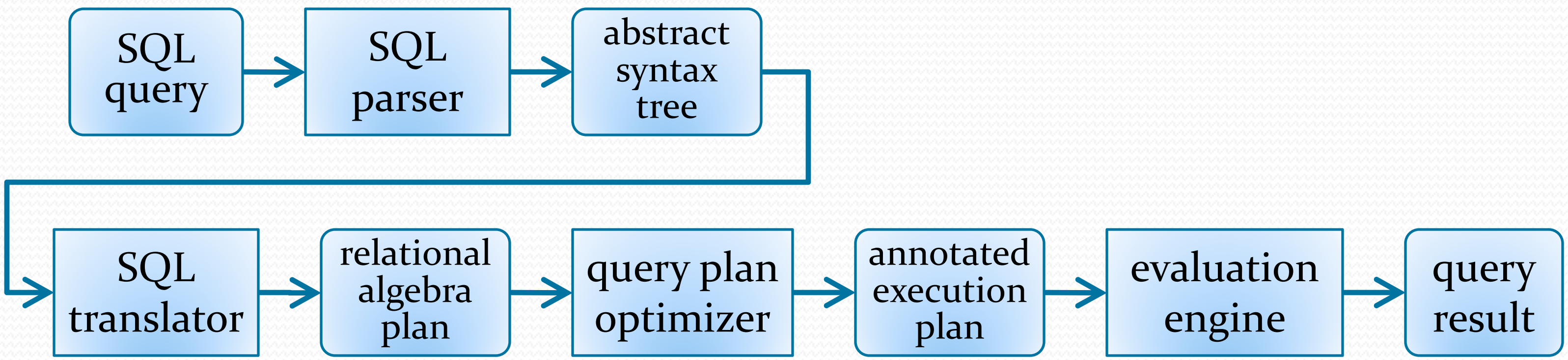
Relational Database System Implementation

CS122 – Lecture 4

Winter Term, 2018-2019

SQL Query Translation

- Last time, introduced query evaluation pipeline



- Queries translated into an abstract syntax tree (AST), then into a plan based on relational algebra primitives
- Optimizations can be applied at AST and/or plan levels
- Evaluation engine executes the plan to produce results

SQL Data Manipulation

- Can handle SELECT, INSERT, UPDATE, DELETE all with same evaluation pipeline
- A good idea anyway, since INSERT, UPDATE, DELETE can all have subqueries in them!

```
INSERT INTO t1 (a, b, c)
    SELECT a, b + 2, c – 5 FROM t2 WHERE d > 5;
UPDATE t1 SET a = a + 5
    WHERE c IN (SELECT c FROM t2);
UPDATE t1 SET a = (SELECT a FROM t2 WHERE t1.b = t2.b);
DELETE FROM t1
    WHERE a = (SELECT MAX(a) FROM t2 WHERE t1.b = t2.b);
```

SQL Data Manipulation (2)

- All four statements generate a set of tuples…
  - Only difference is what we do with them.
  - SELECT selects tuples for display/transmission to client
  - INSERT selects tuples for insertion into a table
  - UPDATE selects tuples for modification
  - DELETE selects tuples for removal
- NanoDB query evaluator takes an execution plan, and a tuple-processor that handles the results
  - For each tuple produced by the execution plan, the tuple-processor does something with the tuple
  - e.g. the TupleUpdater modifies the tuple based on the UPDATE statement issued to the database

SQL Data Manipulation (3)

```
EvalStats QueryEvaluator.executePlan(
    PlanNode plan, TupleProcessor processor)
```

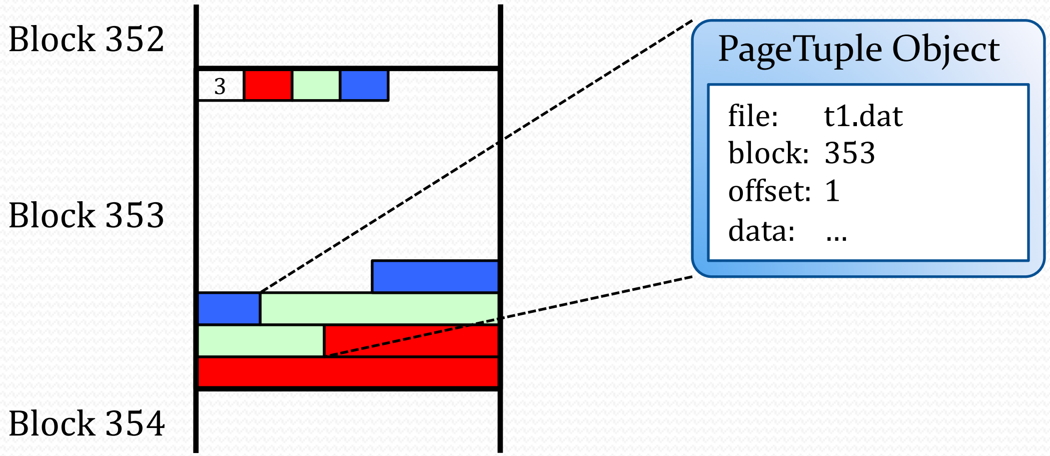
- Evaluator also returns statistics about the evaluation
  - Databases generally tell you how many rows were selected/inserted/updated/deleted, and how long the operation took
- **Not all tuples are created equal!**
  - Some tuples can simply be displayed or sent to client
  - Some tuples must support modification or deletion
  - Databases also have a notion of "l-values" and "r-values"

L-Values and R-Values

- Only certain expressions can be used on the left-hand side of an assignment operation
- Example: `a = 5 + b * 3;`
  - **`a`**, **`b`**, **`5`** and **`3`** are all values
  - Only some of these can be the target of an assignment
- L-values are values with an associated location/address
  - Knowing the location allows us to modify the value
  - "L" indicates it can appear on left-hand side of an assignment
- R-values don't have a location
  - i.e. the value cannot be a target of an assignment operation
  - "R" indicates it must be on right-hand side of the assignment

Kinds of Tuples

- Different flavors of tuples in a database engine
- Some tuples are backed by a page in a database table
  - Reading values from tuple come straight from data page
  - Writing to the tuple modifies the data page in memory
  - (page must then be flushed back to disk)



Kinds of Tuples (2)

- Other tuples contain computed values, and are stored in memory only
  - This query generates computed results:

```
SELECT username, SUM(score) AS total_score
    FROM game_scores GROUP BY username;
```

  - NanoDB represents these as TupleLiteral objects

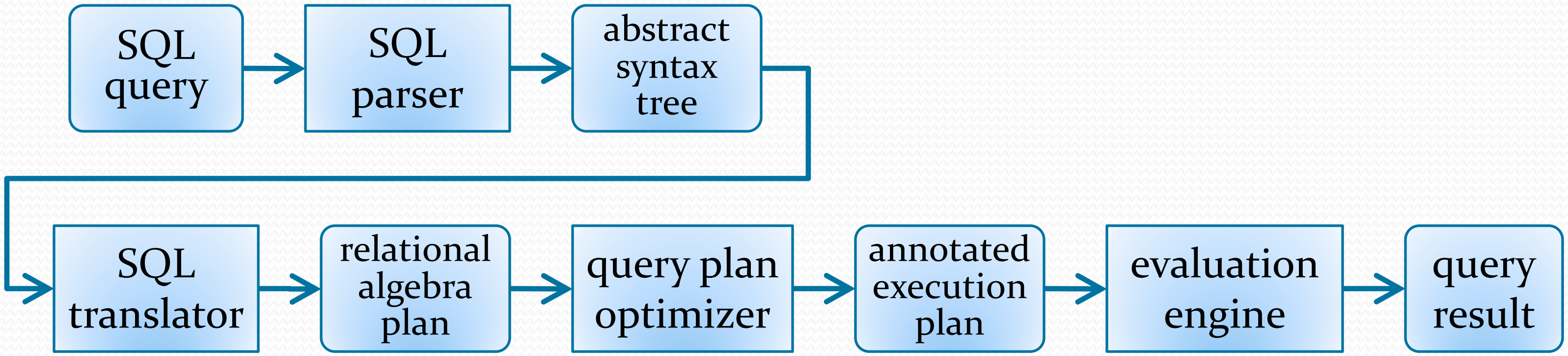
- Many database implementations represent all tuples in the same format, in memory buffers
  - Allows them to be written to disk very easily, if needed

Kinds of Tuples (3)

- SELECT and INSERT…SELECT statements don't require lvalue tuples
  - Results are either displayed, or added to a data file
- UPDATE and DELETE <u>require</u> lvalue tuples
  - Selected tuples are modified or removed!
    - Actually modifies a data file
  - Plans generated for UPDATE and DELETE must take this into account
  - Constrains the optimizations that may be employed

SQL Query Translation

- The query evaluation pipeline:

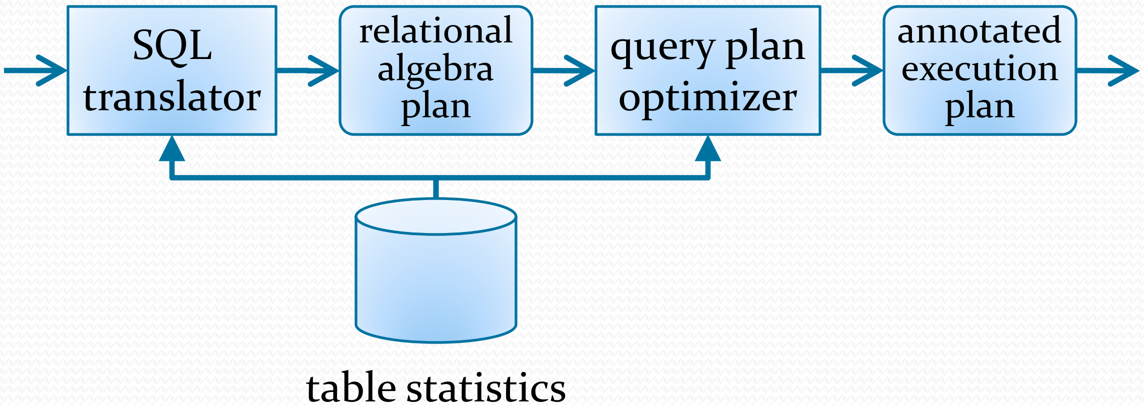


- To evaluate SQL queries, must solve several problems:

1. Implement relational algebra operations in some way
2. Translate the SQL abstract syntax tree (AST) into a corresponding relational algebra plan
3. Figure out how to evaluate plan and generate results

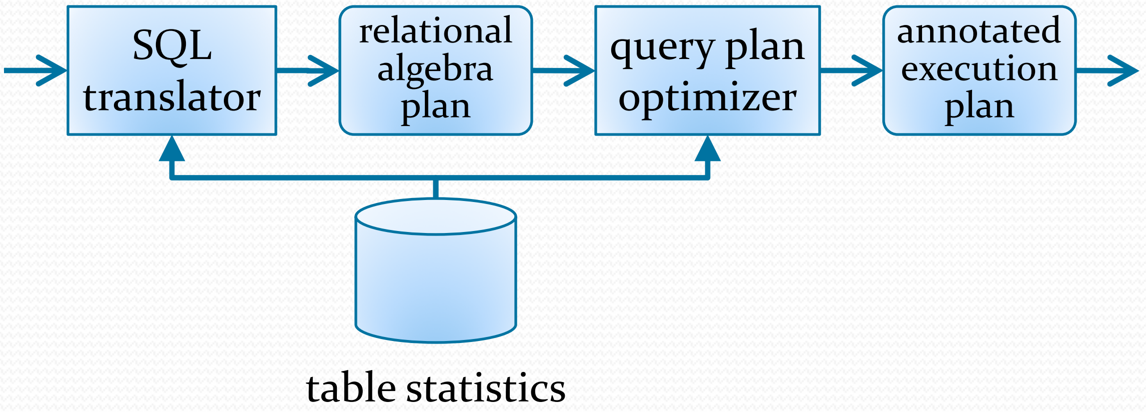
Plan Creation and Optimization

- Some databases use slightly different representations between initial query plan and optimized plan
  - e.g. initial plan uses abstract relational algebra expressions without any implementation details at all
  - Query optimizer adds in these details as annotations
- Annotated plan nodes are called *evaluation primitives*
  - They can be directly used to evaluate the query plan



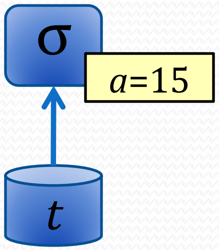
Plan Creation and Optimization

- Other databases use the same representation for both
  - <u>All</u> generated plans contain implementation details
  - Initial query plans may be very unoptimized and use the slowest, most general implementations
  - Optimizations can replace slow implementations with faster ones, and/or apply other transformations
- (NanoDB uses this approach)



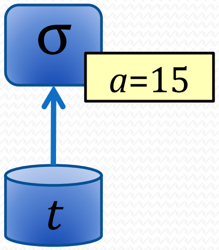
Evaluation Primitives

- Implementations of relational algebra operations are called evaluation primitives
- Don't always correspond directly to relational algebra
- Example:
  - SELECT * FROM t WHERE a = 15
  - $\sigma_{a=15}(t)$
- If t is a heap file:
  - Could create two components, a select node, and another file-scan node that always produces all tuples in t

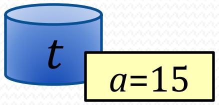


Evaluation Primitives (2)

- Example:
  - SELECT * FROM t WHERE a = 15
  - $\sigma_{a=15}(t)$



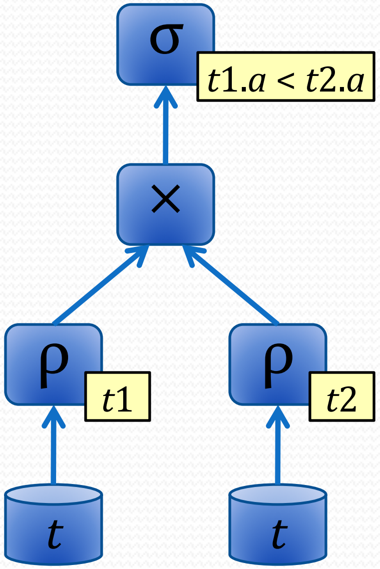
- What if *t* is ordered or hashed on attribute *a*?
  What if *t* has an (ordered or hashed) index on *a*?
  - Can't really take advantage of file organization or other access paths if select-predicate is applied separately



- Can also create a file-scan node with a predicate
- Evaluation primitives are often more powerful than their corresponding relational algebra operations
  - Allows us to optimize the implementations, then use the optimizations when constructing our plans

Evaluation Primitives (3)

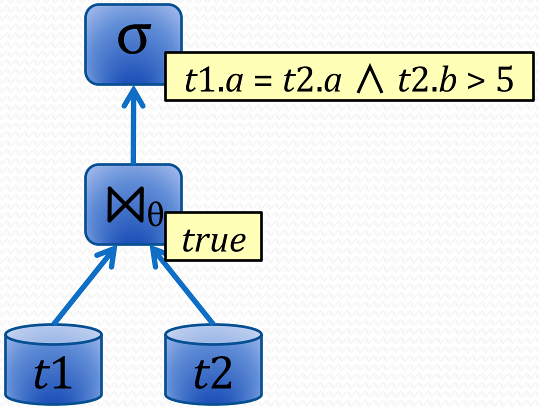
- Example:
  - SELECT * FROM t AS t1, t AS t2
    WHERE t1.a < t2.a
- Table *t* is accessed twice, and is renamed in query plan
- Insert extra rename nodes into plan?
  - Sole operation is to rename table in node's output schema…
  - (This is NanoDB's approach.)

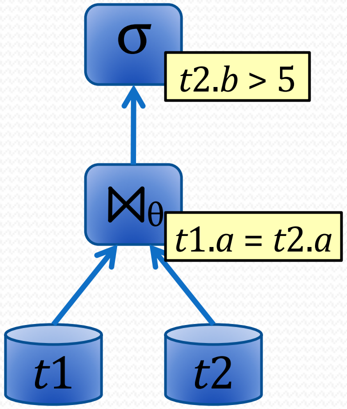


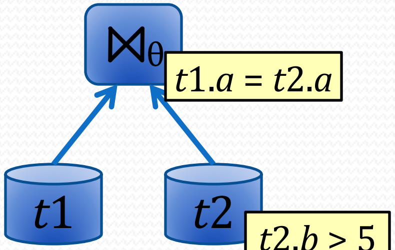
- Or, give plan nodes ability to handle simple renaming ops?
  - When plan nodes produce their schemas, can easily apply renaming at that point

Evaluation Primitives (4)

- Join operations usually implemented with theta-join
  - More advanced/flexible than simple translation using Cartesian product, or simple natural-join operator
  - Implementation can also be configured to produce inner join, or left/right/full outer join, where supported
- SELECT * FROM t1, t2 WHERE t1.a = t2.a AND t2.b > 5;
- Can evaluate in multiple ways:

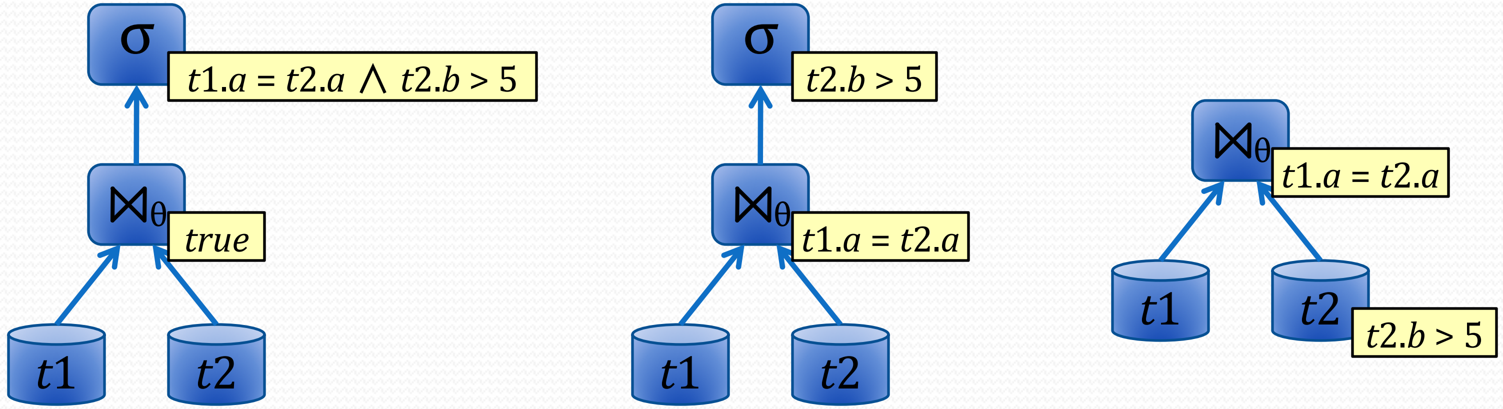






Evaluation Primitives (5)

- SELECT * FROM t1, t2 WHERE t1.a = t2.a AND t2.b > 5;

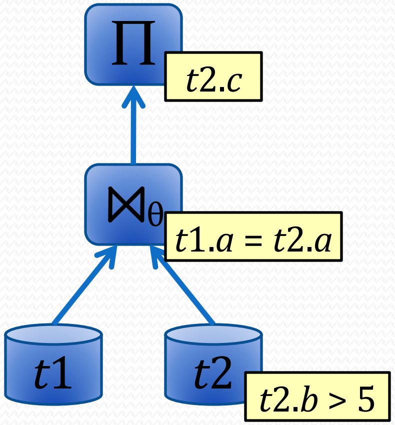


- Ideally, can implement theta-join to take advantage of join condition when possible
  - Perform equijoins more quickly
  - Take advantage of ordered data, or indexes on inputs

Evaluation Primitives (6)

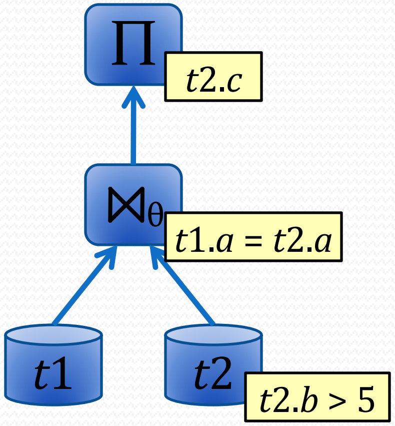
- Many join implementations can do several kinds of join
  - Implement inner join, left outer join, full outer join
  - Implement semijoin and antijoin operations as well (will discuss more in a future lecture)
  - Configure plan node to do the required operation in plan
- By combining multiple operations in plan nodes:
  - Can implement wide range of queries without needing large, complicated plans, or many kinds of plan nodes
  - Can take advantage of certain cases to implement the operation in a much faster way

Plan Evaluation



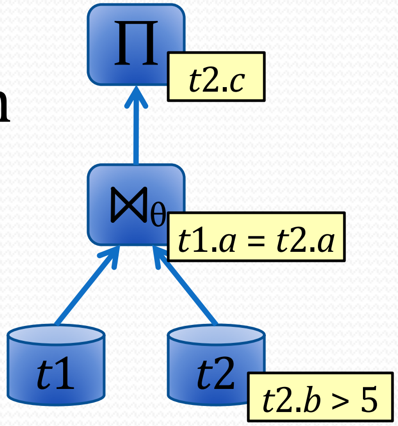
- Previous example, slightly altered:
  - SELECT c FROM t1, t2
    WHERE t1.a = t2.a AND t2.b > 5
- One evaluation approach:
  - Each node is evaluated completely, and its results are saved in a temporary table (postorder tree traversal)
    - "Evaluate" $t1 \rightarrow t1$ (no-op)
    - Evaluate $\sigma_{b>5}(t2) \rightarrow temp1$
    - Evaluate $\bowtie_{t1.a=t2.a}(t1, temp1) \rightarrow temp2$
    - Evaluate $\Pi_{t2.c}(temp2) \rightarrow$ result

Plan Evaluation (2)



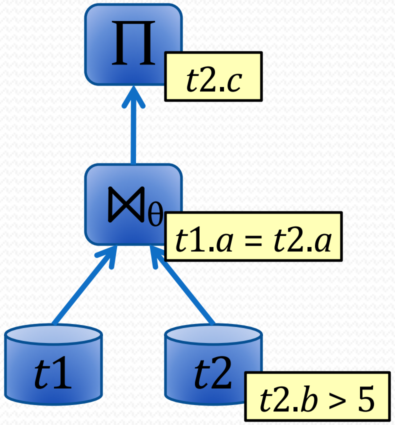
- Called *materialized evaluation*
  - Each node's results are *materialized* into a temporary table (possibly onto disk)
- Issues with this approach?
  - For large tables, causes many <u>additional</u> disk accesses on top of ones already required for plan-node evaluation!
  - (Small temporary results can be held in memory.)
- Another evaluation approach: *pipelined evaluation*
  - Evaluate multiple plan nodes simultaneously
  - Results are passed tuple-by-tuple to the next plan node

Plan Evaluation (3)



- Several ways to implement pipelined evaluation
- *Demand-driven* pipeline:
  - Rows are requested (pulled) from top of plan
  - When a plan-node must produce a row, it requests rows from its child nodes until it can produce one
- Example:
  - Top-level output loop requests a row from $\Pi_{t2.c}$ node
  - $\Pi_{t2.c}$ node requests the next row from $\bowtie_{t1.a=t2.a}$ node
  - $\bowtie_{t1.a=t2.a}$ node requests rows from its children until it can produce a joined row
  - $\sigma_{t2.b>5}$ node scans through $t2$ until it finds a row with $b > 5$

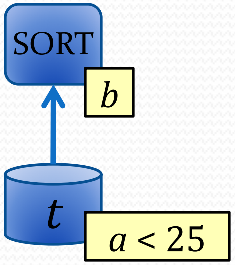
Plan Evaluation (4)



- *Producer-driven* pipeline:
  - Each plan-node independently generates rows and pushes them up the plan
  - Plan nodes communicate via queues
- Primarily used in parallel databases
  - Planner hands subplans (or individual plan nodes) to different processors to compute
  - Processors independently evaluate plan components and push tuples to the next stage in the plan
- Sequential databases generally use demand-driven pipelines for query evaluation

Blocking Operations

- Not all operations can be pipelined
- An obvious one: sorting
  - SELECT * FROM t WHERE a < 25 ORDER BY b;
  - Sort plan-node must completely consume its input before it can produce any rows



- These are called *blocking operations*
- Some databases take blocking operations into account
  - e.g. PostgreSQL's planner computes two estimates for each plan node:
    - the cost to produce all rows
    - the cost to produce the first row
  - For e.g. EXISTS subquery, want to minimize time to first row

Blocking Operations (2)

- Some operations can be implemented in blocking or in pipelined ways
- Grouping/aggregation operation
  - SELECT username, SUM(score) AS total_score FROM game_scores GROUP BY username;
  - $_{username}\mathcal{G}_{\textbf{sum}(score)\ \textbf{as}\ total\_score}(game\_scores)$
- If incoming tuples are already sorted on *username*:
  - Can apply aggregate function to runs of tuples with same *username* value, and produce output rows along the way
- If incoming tuples are not sorted on *username*:
  - Must either use a hash-table, or must sort internally
  - Either way, the operation will be blocking

SQL Query Translation (2)

- For now, ignore the question of how to implement specific relational algebra operations
  - (Most are straightforward anyway)
- SQL doesn't map directly to the relational algebra
  - Nested subqueries!!!! Correlated evaluation!!!!
  - Grouping and aggregation is also complicated
- Basic SQL syntax maps easily to relational algebra
  - Explored this in CS121

Mapping Basic SQL Queries

- SELECT * FROM t1, t2, …
  - $t1 \times t2 \times \ldots$
- SELECT * FROM t1, t2, … WHERE P
  - $\sigma_P(t1 \times t2 \times \ldots)$
- SELECT e1 AS a1, e2 AS a2, … FROM t1, t2, …
  - $e1, e2, \ldots$ are expressions using columns in $t1, t2, \ldots$
  - $a1, a2, \ldots$ are aliases (alternate names) for $e1, e2, \ldots$
  - $\Pi_{e1 \text{ as } a1, e2 \text{ as } a2, \ldots}(t1 \times t2 \times \ldots)$
- SELECT e1 AS a1, e2 AS a2, … FROM t1, t2, … WHERE P
  - $\Pi_{e1 \text{ as } a1, e2 \text{ as } a2, \ldots}(\sigma_P(t1 \times t2 \times \ldots))$

Mapping Basic SQL Queries (2)

- SELECT e1 AS a1, e2 AS a2, … FROM t1, t2, … WHERE P
  - $\Pi_{e1,e2,\ldots}(\sigma_P(t1 \times t2 \times \ldots))$
- This mapping is somewhat confusing, because many DBs accept queries that don't work with this translation
- Example: SELECT a + c AS v FROM t WHERE v < 25;
  - Following the above mapping: $\Pi_{a+c\ \mathbf{as}\ v}(\sigma_{v<25}(t))$
  - Doesn't make sense; *v* isn't defined in select predicate!

- The SQL standard is very clear (and simple!):
  - P is only allowed to refer to columns in the FROM clause
  - (ignoring correlated evaluation for the time being)

Mapping Basic SQL Queries (3)

- Can easily support non-standard syntax by recording select-clause aliases in the AST representation
- Example: SELECT a + c AS v FROM t WHERE v < 25;
  - Traverse SELECT clause; record alias: $v = a + c$
  - In the WHERE predicate: anytime v is used, replace it with expression $a + c$
    - Also do this with ON clauses in joins, HAVING clauses, etc.
  - Allows us to follow previous mapping: $\Pi_{a+c \textbf{ as } v}(\sigma_{a+c<25}(t))$
- Other techniques as well, but same idea

SQL Grouping/Aggregation

- Grouping and aggregation are significantly more difficult
- SELECT g1, g2, ..., e1, e2, ... FROM t1, t2, ... WHERE Pw GROUP BY g1, g2, ... HAVING Ph
  - $g1, g2$, ... are expressions whose values are grouped on
  - $e1, e2$, ... are expressions involving aggregate functions
    - e.g. MIN(), MAX(), COUNT(), SUM(), AVG()
  - Approximately maps to: $\sigma_{Ph}({}_{g1,g2,\ldots}\mathcal{G}_{e1,e2,\ldots}(\sigma_{Pw}(t1 \times t2 \times \ldots)))$
- What makes this challenging:
  - $g1, g2$, ... are not required to be simple column refs
  - $e1, e2$, ... are not required to be single aggregate fns
  - *Ph* can also contain aggregate function calls not in e_i

SQL Grouping/Aggregation (2)

- This is an acceptable grouping/aggregate query:
  - SELECT a - b AS g, 3 * MIN(c) + MAX(d * e) FROM t GROUP BY a - b HAVING SUM(f) < 20
- Clearly can't use our mapping from last slide:
  - $\sigma_{Ph}({}_{g1,g2,\ldots}\mathcal{G}_{e1,e2,\ldots}(\sigma_{Pw}(t1 \times t2 \times \ldots)))$
  - e.g. *Ph* is SUM(f) < 20, but we don't compute SUM(f) in $\mathcal{G}$ step
- Problem: SQL mixes grouping/aggregation, projection and selection parts of the query together
- Need to rewrite query to separate these different parts
  - Makes translation into relational algebra straightforward