CS525: Advanced Database Organization

Notes 6: Query Processing
Part III: Convert Parse Tree into initial L.Q.P

Yousef M. Elmehdwi

Department of Computer Science

Illinois Institute of Technology

yelmehdwi@iit.edu

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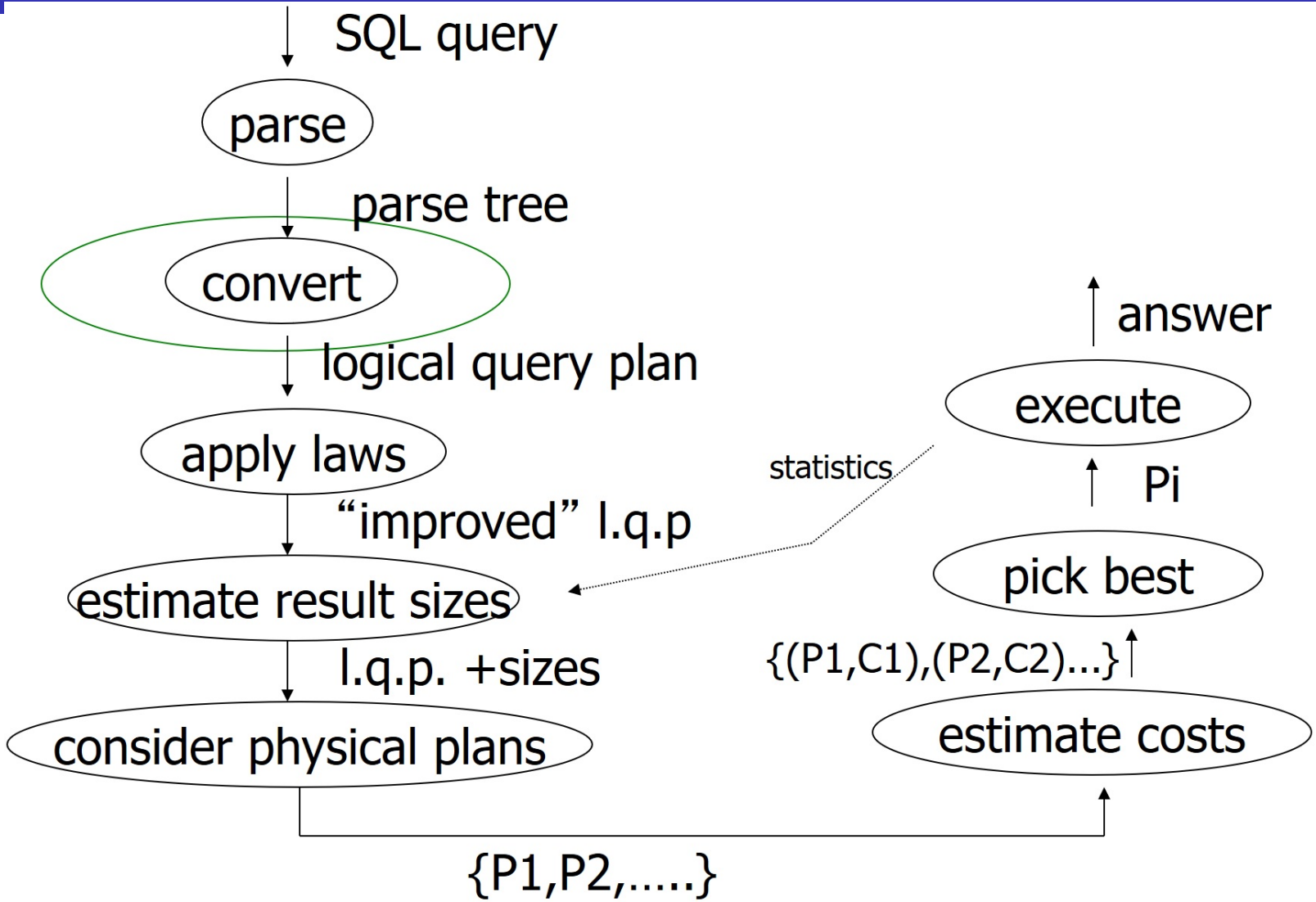
Where we are?



- *Note: when we have executed the query, it might be wise to give statistics back to LQP-rewrite components or components estimating size to perform later operations like join in a cost-efficient order*

Today

- Convert the parse query tree to an initial query plan, which is usually an algebraic representation of the query (relational algebra expression)

Relation Schema, Relation Instance, Tuple

- `Relation`
  - Unordered set that contain the relationship of attributes that represent entities.
- `Tuple`
  - Set of attribute values (also known as its domain) in the relation/row of values of the relation (table).
    - Values are normally atomic/scalar.
    - The special value NULL is a member of every domain.
- `Relation Schema`
  - A set of attribute name-datatype pairs
  - Schema for a relation defined the names of the attributes and the domain for the attributes

Conversion

- *Much of query optimization relies on the underlying concept that the high level properties of relational algebra are preserved across equivalent expressions. Two relational algebra expressions are equivalent if they generate the same set of tuples.*
- Create an internal representation
  - Should be useful for analysis
  - Should be useful optimization
- Internal representation
  - Relational algebra

Relational Algebra Recap

- A set of fundamental operations to retrieve and manipulate tuples in a relation.
  - i.e., mathematical language for manipulating sets
  - based on set algebra
- An algebra whose operands are relations or variables that represent relations.
- Operators are designed to do the most common things that we need to do with relations in a database.
  - The result is an algebra that can be thought of as an abstract query language for relations.
- Each operator takes one or more relations as its inputs and outputs a new relation.
  - To write queries, we can chain these operators together to create more complex operations.

Set- vs. Bag semantics

- Set and Bag semantics version
  - *Set: a collection of elements that do not contain duplicate elements*
  - *Bag: a collection of elements that can contain duplicate elements*
- Relational Algebra has two semantics:
  - Set semantics: Relations are Sets of tuples, which by definition do not contain "duplicate" entries
  - Bag semantics: Relations are Multi-Sets where each element (tuple) can appear more than once
    - duplicates are not eliminated
- SQL uses bag semantics
- If we use bag semantics, we may have to redefine the meaning of each relation algebra operator

Set- vs. Bag semantics

Set

Name	Purchase
Peter	Guitar
Joe	Drum
Alice	Bass

Bag

Name	Purchase
Peter	Guitar
Peter	Guitar
Joe	Drum
Alice	Bass
Alice	Bass

Why Bags?

- SQL, the most important query language for relational databases is actually a bag language.
  - SQL will eliminate duplicates, but usually only if you ask it to do so explicitly.
- Some operations, like projection or union, are much more efficient on bags than sets
  - Selection applies to each tuple, so its effect on bags is like its effect on sets.
  - Projection also applies to each tuple, but as a bag operator, we do not eliminate duplicates.
  - Products and joins are done on each pair of tuples, so duplicates in bags have no effect on how we operate

Bag semantics notation

- We use t^m to denote tuple t appears with multiplicity m

Operators

- `Selection`
- `Renaming`
- `Projection`
- `Joins`
  - Theta, natural, cross-product, outer, anti
- `Aggregation`
- `Duplicate removal`
- `Set operations`

Selection Operation (σ)

- Choose a subset of the tuples from a relation that satisfies a selection predicate.
  - Predicate acts as a filter to retain only tuples that fulfill its qualifying requirement.
  - Can combine multiple predicates using conjunctions / disjunctions.
- `Syntax:` $\sigma_{\texttt{c}}(\texttt{R})$
  - `R` is input
  - `c` is a condition (called the selection predicate)
- Semantics:
  - Return all tuples that match condition `c`
  - `Set:` $\{\ \texttt{t} \mid \texttt{t} \in \texttt{R AND t fulfills c}\}$
  - `Bag:` $\{\ \texttt{t}^n \mid \texttt{t}^n \in \texttt{R AND t fulfills c}\}$
    - process each tuple independently; a tuple may appear in the resulting relation multiple times.

Select: Example

- $\sigma_{a>5}(\mathtt{R})$

R

a	b
1	13
3	12
6	14

Result

a	b
6	14

Projection operation (π)

- Generate a relation with tuples that contains only the specified attributes.
  - Can rearrange attributes' ordering.
  - Can manipulate the values.
- `Syntax:` $\pi_{\texttt{A}}(\texttt{R})$
  - `R` is input
  - `A` is list of projection expressions (attribute list)
    - The attribute-list `A` contains the list of attributes in relation `R` that will be selected.
- Semantics:
  - Select out only the attribute values given in the attribute-list `A` from all tuples in relation `R`
  - `Set:` $\{\ \texttt{t.A}\ \mid\ \texttt{t} \in \texttt{R}\}$
  - `Bag:` $\{\ (\texttt{t.A})^n\ \mid\ \texttt{t}^n \in \texttt{R}\}$
    - process each tuple independently; a tuple may appear in the resulting relation multiple times

Projection: Example

- $\pi_b(\mathtt{R})$

R

a	b
1	13
3	12
6	14

Result

b
13
12
14

Compose: Select and Project

- to pick both columns and rows, we can compose operators
- $\pi_{\texttt{A}_1,\texttt{A}_2,\ldots,\texttt{A}_n}(\sigma_{\texttt{condition}}(\texttt{Expression}))$

Renaming

- To unify schemas for set operators
- For disambiguation in "self-joins"
- `Syntax:` $\rho_{\texttt{A}}(\texttt{R})$
  - `R` is input
  - `A` is list of attribute renaming `b`$\leftarrow$`a`
- Semantics:
  - Applies renaming from `A` to inputs
  - `Set:` $\{\ \texttt{t.A} \mid \texttt{t} \in \texttt{R}\}$
  - `Bag:` $\{\ (\texttt{t.A})^n \mid \texttt{t}^n \in \texttt{R}\}$

Renaming: Example

- $\rho_{c \leftarrow a}(\mathtt{R})$

R

a	b
1	13
3	12
6	14

Result

c	b
1	13
3	12
6	14

Cross Product

- Combine two relations (a.k.a Cartesian product/Cross Join)
- Generate a relation that contains all possible combinations of tuples from the input relations.
- `Syntax:` $\texttt{R} \times \texttt{S}$
  - `R` and `S` are inputs
- Semantics:
  - All combinations of tuples from `R` and `S`
  - = mathematical definition of **`cross product`**
  - `Set:` $\{ \texttt{(t,s)} \mid \texttt{t} \in \texttt{R AND s} \in \texttt{S} \}$
  - `Bag:` $\{ \texttt{(t,s)}^{n \times m} \mid \texttt{t}^{n} \in \texttt{R AND s}^{m} \in \texttt{S} \}$

- The cartesian product will produce many meaningless results

Cross Product: Example

- R × S

R

a	b
1	13
3	12

S

c	d
a	5
b	3
c	4

Result

a	b	c	d
1	13	a	5
1	13	b	3
1	13	c	4
3	12	a	5
3	12	b	3
3	12	c	4

Join Types

- Cross Join
  - Same thing as Cartesian product.
- Inner Join
  - Each tuple in the first relation must have a corresponding match in the second relation.
  - Natural Join, Theta/Equi Join, Semi Join, Anti Join.
- Outer Join
  - Each tuple in the one relation does not need to have a corresponding match in the other relation.

Condition/Theta Join operation

- Combine related tuples from two relations
- Match tuples using some arbitrary join predicate defined by θ
  - If θ is just an equality predicate, then it is called an Equi Join.
- `Syntax:` $\texttt{R} \bowtie_\theta \texttt{S}$
  - `R` and `S` are inputs
  - θ is a condition
- Semantics:
  - All combinations of tuples from `R` and `S` that match θ
  - `Set:` $\{ \texttt{(t,s) | t} \in \texttt{R AND s} \in \texttt{S AND (t,s) matches } \theta \}$
  - `Bag:` $\{ \texttt{(t,s)}^{n \times m} \texttt{ | t}^{n} \in \texttt{R AND s}^{m} \in \texttt{S AND (t,s) matches } \theta \}$

- The `condition join` operation is a shorthand notation for the following
  - $\texttt{R} \bowtie_\theta \texttt{S} = \sigma_\theta(\texttt{R} \times \texttt{S})$

Condition/Theta Join: Example

- $R \bowtie_{a=d} S$

R

a	b
1	13
3	12

S

c	d
a	5
b	3
c	4

Result

a	b	c	d
3	12	b	3

Natural Join

- Generate a relation that contains all tuples that are a combination of two tuples (one from each input relation) with a common value(s) for one or more attributes.
  - Enforce equality on all attributes with same name (The name and type of the attribute must be same).
- Eliminate one copy of duplicate attributes
- `Syntax:` $\texttt{R} \bowtie \texttt{S}$
  - `R` and `S` are inputs
- Semantics:
  - All combinations of tuples from `R` and `S` that match on common attributes
  - `A` = common attributes of `R` and `S`
  - `B` = exclusive attributes of `S`
  - `Set:` $\{\texttt{(t,s.B) | t} \in \texttt{R AND s} \in \texttt{S AND t.A=s.A}\}$
  - `Bag:` $\{\texttt{(t,s.B)}^{n \times m} \texttt{ | t}^{n} \in \texttt{R AND s}^{m} \in \texttt{S AND t.A=s.A}\}$

- The natural join operation is a shorthand notation for the following
  - $\texttt{R} \bowtie \texttt{S} = \pi_{\texttt{L}}\left(\sigma_{\texttt{R.A=S.A}}(\texttt{R} \times \texttt{S})\right)$, `where` $L = (list\ of\ attribues\ in\ R) \cup B$

Natural Join: Example

- R ⋈ S

R

a	b
1	13
3	12

S

c	a
a	5
b	3
c	4

Result

a	b	c
3	12	b

Left-outer Join

- Outer Join: Retain information that would have been lost from the relations, replacing missing data with NULLs
- Left-outer Join: keep data from the left-hand relation
- `Syntax:` $R \ltimes\!\!\!\rightarrow_c S$
  - `R` and `S` are inputs
  - `c` is condition
- Semantics:
  - Contains all tuples in `R` join `S`
  - Also includes every tuple in `R` that is not joined with a tuple in `S`, after padding a `NULL` (`t`$\in$`R` without match, fill `S` attributes with `NULL`)

```
{(t,s) | t∈R AND s∈S matches c}
union
{(t,NULL(S))| t∈R AND NOT exists s∈S: (t,s) matches c}
```

Left-outer Join: Example

- R $\ltimes\!\!\!\bowtie_{a=d}$ S

R

a	b
1	13
3	12

S

c	d
a	5
b	3
c	4

Result

a	b	c	d
1	13	NULL	NULL
3	12	b	3

Right-outer Join

- Right-outer Join: keep data from the right-hand relation
- `Syntax:` $R \rtimes_c S$
  - `R` and `S` are inputs
  - `c` is condition
- Semantics:
  - `R` join `S`
  - `s`$\in$`S` without match, fill `R` attributes with `NULL`

```
{(t,s) | t∈R AND s∈S matches c}
union
{(NULL(R),s)| s∈S AND NOT exists t∈R: (t,s) matches c}
```

Right-outer Join: Example

- $\mathtt{R} \rtimes\!\!\!\!\!\!\subset_{a=d} \mathtt{S}$

R

a	b
1	13
3	12

S

c	d
a	5
b	3
c	4

Result

a	b	c	d
NULL	NULL	a	5
3	12	b	3
NULL	NULL	c	4

Full-outer Join

- Full-outer Join: keep data from both relations
- `Syntax:` $\texttt{R} \mathbin{⟗_{\texttt{c}}} \texttt{S}$
  - `R` and `S` are inputs
  - `c` is condition
- Semantics:

```
{(t,s) | t∈R AND s∈S AND (t,s) matches c}
union
{(NULL(R),s)| s∈S AND NOT exists t∈R: (t,s) matches c}
union
{(t,NULL(S))| t∈R AND NOT exists s∈S: (t,s) matches c}
```

Full-outer Join: Example

- R $\overset{\subset}{\bowtie}_{a=d}$ S

R

a	b
1	13
3	12

S

c	d
a	5
b	3
c	4

Result

a	b	c	d
1	13	NULL	NULL
NULL	NULL	a	5
3	12	b	3
NULL	NULL	c	4

Aggregation

- Operators that summarize or aggregate the values in a single attribute of a relation
- Operators are the same in relational algebra and SQL.
- All operators treat a relation as a bag of tuples.
- SUM: computes the sum of a column with numerical values.
- AVG: computes the average of a column with numerical values.
- MIN and MAX:
  - for a column with numerical values, computes the smallest or largest value, respectively.
  - for a column with string or character values, computes the lexicographically smallest or largest values, respectively
- COUNT: computes the number of non-NULL tuples in a column.
  - In SQL, can use COUNT (*) to count the number of tuples in a relation
  - Null values counted by COUNT(*), discarded by other aggregate operators.

Aggregation

- Grouping and aggregation generally need to be implemented and optimized together
- `Syntax:` $_{\texttt{G}}\gamma_{\texttt{A}}(\texttt{R})$
  - `A` is list of aggregation functions
  - `G` is list of group by attributes
- Semantics:
  - Build groups of tuples according `G` and compute the aggregation functions from each group

  - {t.G, agg(G(t)) | t∈R}
  - G(t) = {t' | t'∈R AND t'.G = t.G}

Aggregation: Example

- $_b\gamma_{sum(a)}$(R)

R

a	b
1	1
3	1
6	2
3	2

Result

sum(a)	b
4	1
9	2

Duplicate Removal/Elimination

- `Syntax:` δ`(R)`: is the relation containing exactly one copy of each tuple in `R`
  - `R` is input
- Semantics:
  - Remove duplicates from input
  - `Set:` N/A
  - `Bag:` $\{\mathtt{t}^1 \mid \mathtt{t}^n \in \mathtt{R}\}$
- Duplicate elimination is expensive, since tuples must be sorted or partitioned.

Duplicate Removal

- $\delta(\mathtt{R})$

R

a	b
1	13
1	13
6	14

Result

a	b
1	13
6	14

Union, Intersection, and Difference

- Union, intersection, and difference need new definitions for bags.
- Input: `R` and `S`
  - Have to have the same schema
    - Union compatible: two relations have the same schema: exactly same attributes drawn from the same domain

Union

- Syntax: $R \cup S$
  - Generate a relation that contains all tuples that appear in either only one or both input relations.
  - R and S are union-compatible inputs
- Semantics:
  - Set: $\{t \mid t \in R \text{ OR } t \in S\}$
  - Bag:
    - An element appears in the union of two bags the sum of the number of times it appears in each bag.
    - $\{(t,s)^{n+m} \mid t^n \in R \text{ AND } s^m \in S\}$
    - e.g., $\{1,2,1\} \cup \{1,1,2,3,1\} = \{1,1,1,1,1,2,2,3\}$

Union: Example

- R ∪ S

R

a
1
3

S

b
1
2
3

Result

a
1
2
3
1
3

Intersection

- Syntax: $R \cap S$
  - Generate a relation that contains only the tuples that appear in both of the input relations
  - R and S are union-compatible inputs
- Semantics:
  - Set: $\{t \mid t \in R \text{ AND } t \in S\}$
  - Bag: $\{(t,s)^{min(n,m)} \mid t^n \in R \text{ AND } s^m \in S\}$
    - An element appears in the intersection of two bags the minimum of the number of times it appears in either
    - $\{1,2,1,1\} \cap \{1,2,1,3\} = \{1,1,2\}$

Intersection: Example

- R ∩ S

R

a
1
3

S

b
1
2
3

Result

a
1
3

Set Difference

- Syntax: `R − S`
  - Generate a relation that contains only the tuples that appear in the first and not the second of the input relations.
  - `R` and `S` are union-compatible inputs
- Semantics:
  - Set: $\{$`t | t∈R AND NOT t∈S`$\}$
  - Bag: $\{$`(t,s)`$^{max\{0,n-m\}}$ `| t`^{n} `∈R AND s`^{m} `∈S`$\}$
    - An element appears in the difference `R − S` of bags as many times as it appears in `R`, minus the number of times it appears in `S`.
      - *But never less than 0 times.*
    - `{1,2,1,1} − {1,2,3} = {1,1}`

Set Difference: Example

- `R - S`

R

a
1
5

S

b
1
2
3

Result

a
5

- `Logical Query Plan (LQP) Generation`
  - Converting a Parse Tree into an initial logical query plan (tree)

Conversion into Relational Algebra

- When the query is expressed as a valid parse tree, we can generate a LQP expressed by relational algebra operators
- SFW without sub-queries:
  - replace the relations in the `<FromList>` by the product, $\times$, of all relations
  - this product is the argument of a selection, $\sigma_{\texttt{C}}$, where `C` is the `<Condition>` expression being replaced
  - this selection is in turn the argument of a projection, $\pi_{\texttt{L}}$, where `L` is the list of attributes in the `<SelList>`

Canonical Translation to Relational Algebra

- TEXTBOOK version of conversion
- Given an `SQL` query
- Return an equivalent relational algebra expression

Canonical Translation to Relational Algebra

- **FROM** clause into joins and crossproducts
- **WHERE** clause into selection
- **SELECT** clause into projection and renaming
  - If it has aggregation functions use aggregation
  - **DISTINCT** into duplicate removal
- **GROUP BY** clause into aggregation
- **HAVING** clause into selection
- **ORDER BY** - no counter-part
  - Since a relation is a set (or a bag), there is no ordering defined for a relation. That is, two relations are the same if they contain the same tuples, irrespective of ordering.

Set Operations

- **UNION ALL** into union
- **UNION** duplicate removal over union
- **INTERSECT ALL** into intersection
- **INTERSECT** add duplicate removal
- **EXCEPT ALL** into set difference
- **EXCEPT** apply duplicate removal to inputs and then apply set difference

Logical and physical query plans

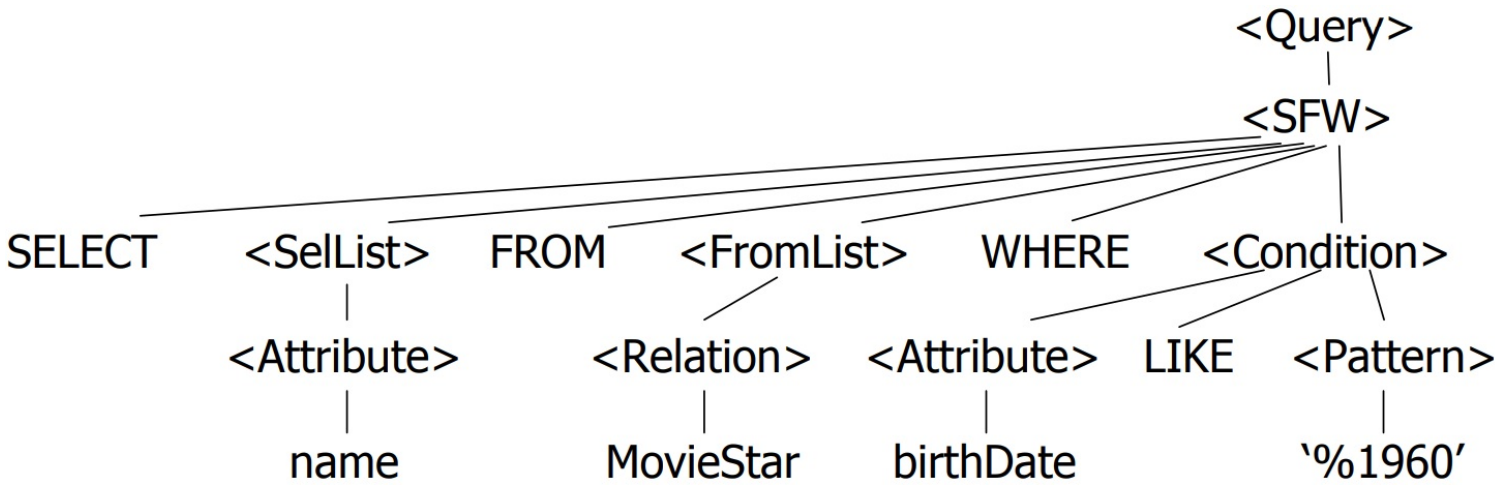
- Both are trees representing query evaluation
- Leaves represent data
- Internal nodes are operators over the data
- Logical plan is higher-level and algebraic
- Physical plan is lower-level and operational

Expression Trees

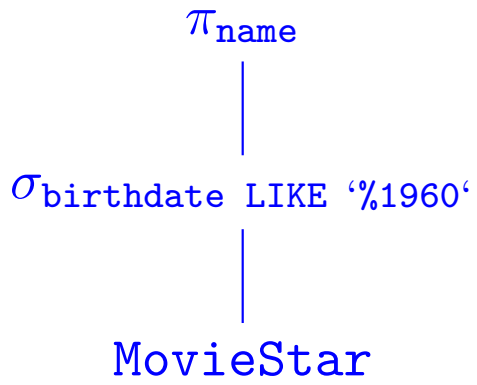
- Expression tree is a binary tree in which each internal node corresponds to operator and each leaf node corresponds to operand
- Leaves are operands
  - Interior nodes are operators, applied to their child or children.

Conversion into Relational Algebra: Example 1

```
SELECT name FROM MovieStar WHERE birthdate LIKE '%1960';
```

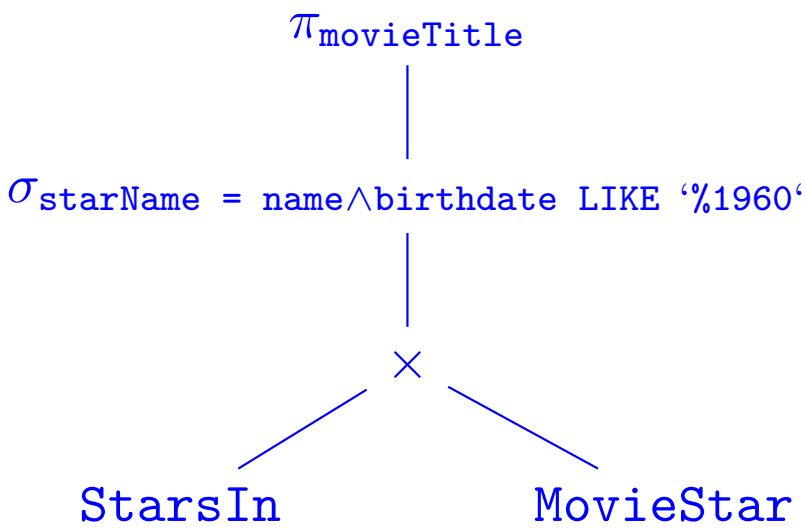


- product of relations in `<FromList>`
- select tuples using expression in `<Condition>`
- project wanted attributes in the `<SelList>`



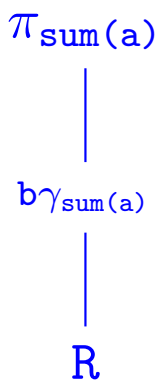
Conversion into Relational Algebra: Example 2

```
SELECT movieTitle
FROM   StarsIn, MovieStar
WHERE  starName = name AND birthdate LIKE '%1960';
```



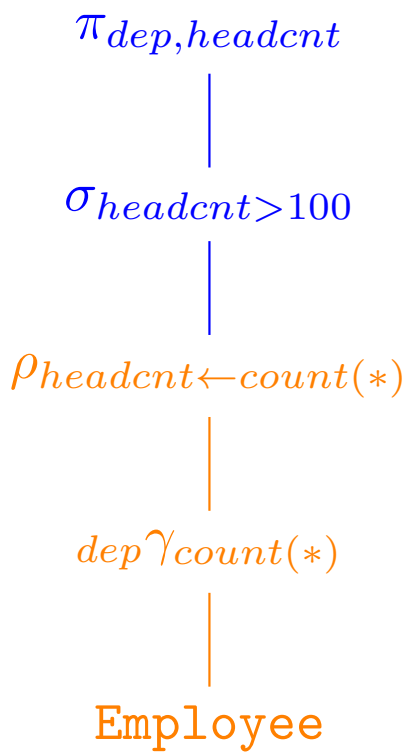
Conversion into Relational Algebra: Example 3

```
SELECT sum(a)
FROM R
GROUP BY b
```



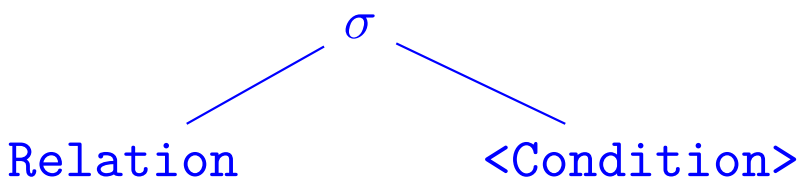
Conversion into Relational Algebra: Example 4

```
SELECT dep, headcnt
FROM (SELECT count(*) AS headcnt, dep
                  FROM Employee
                  GROUP BY dep)
WHERE headcnt > 100
```



Conversion into Relational Algebra

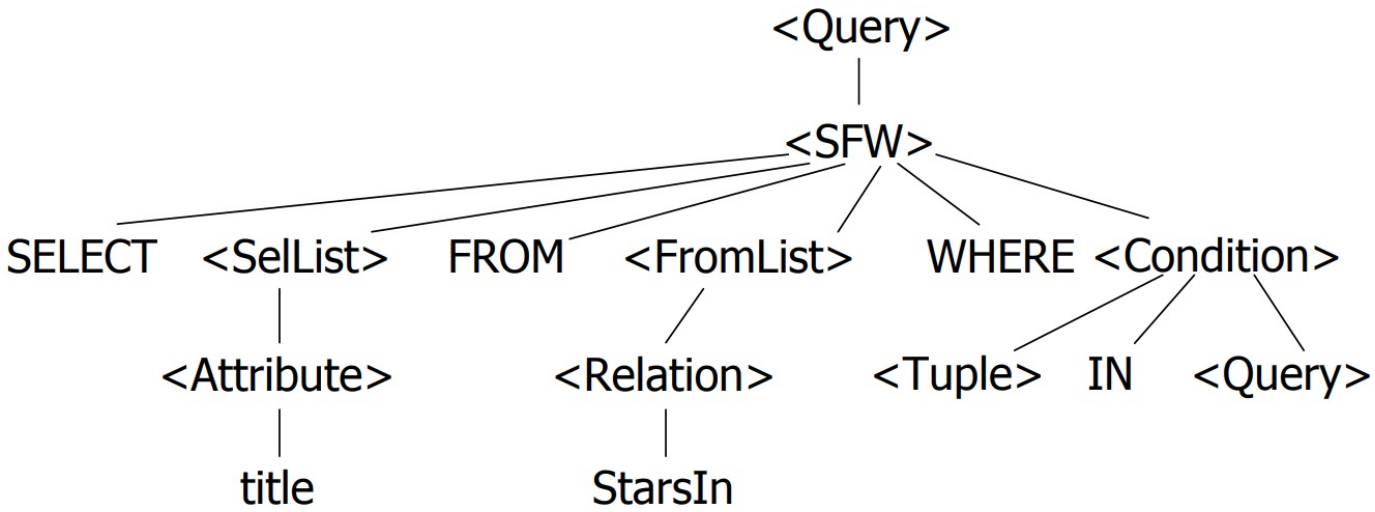
- If we have `sub-queries`, we must remove them by using an intermediate operator - `two argument select` σ:



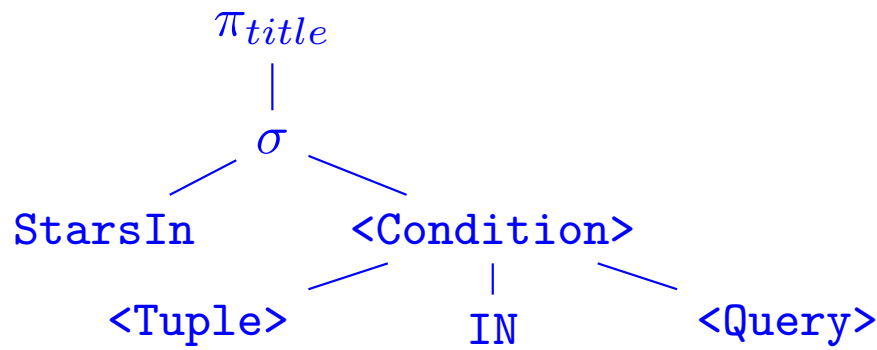
  - left child represents relation upon which the selection is performed
  - right child is an expression for the condition applied to each tuple of the relation

Conversion into Relational Algebra: Example 5

```
SELECT title FROM StarsIn WHERE starName IN (<Query>);
```



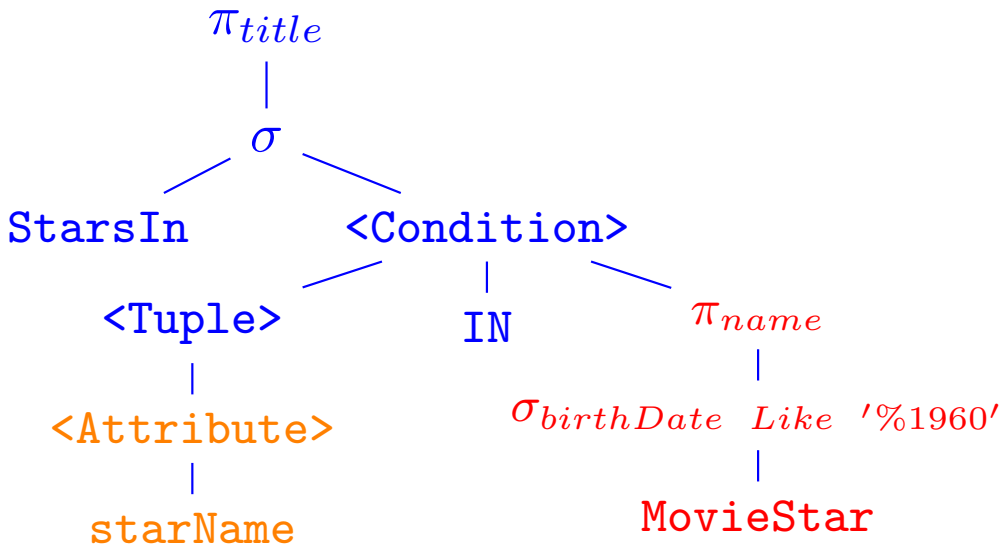
- product of relations in `<FromList>`
- select tuples using expression in `<Condition>`, but use the `two-argument select` on sub-query
- project wanted attributes in the `<SelList>`



Conversion into Relational Algebra: Example 5(Cont.)

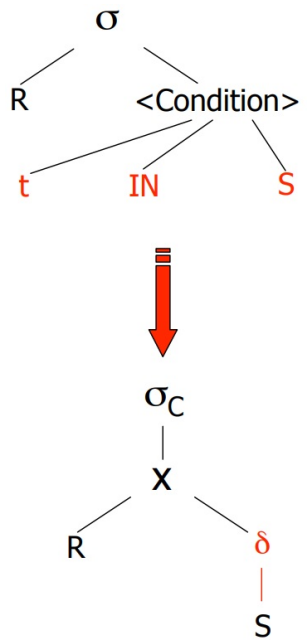
```
SELECT title FROM StarsIn WHERE starName IN (<Query>);
```

- `<Tuple>` is represented by `<Attribute>` – *starName*
- the sub-query `<Query>` is the query we converted earlier
- This tree needs further transformation



Conversion into Relational Algebra

- Replace `two-argument select`:
  - different conditions require different rules
  - we will look at `t IN S`:
  - replace `<Condition>` with the tree representing `S`. If `S` may have duplicates we must include a δ-`operator` at the top
  - replace the `two-argument selection` by a `one-argument selection` σ_C, where `C` is the condition that equates each component of tuple `t` to the corresponding attribute in `S`
  - give σ_C an argument that is the product of `R` and `S`

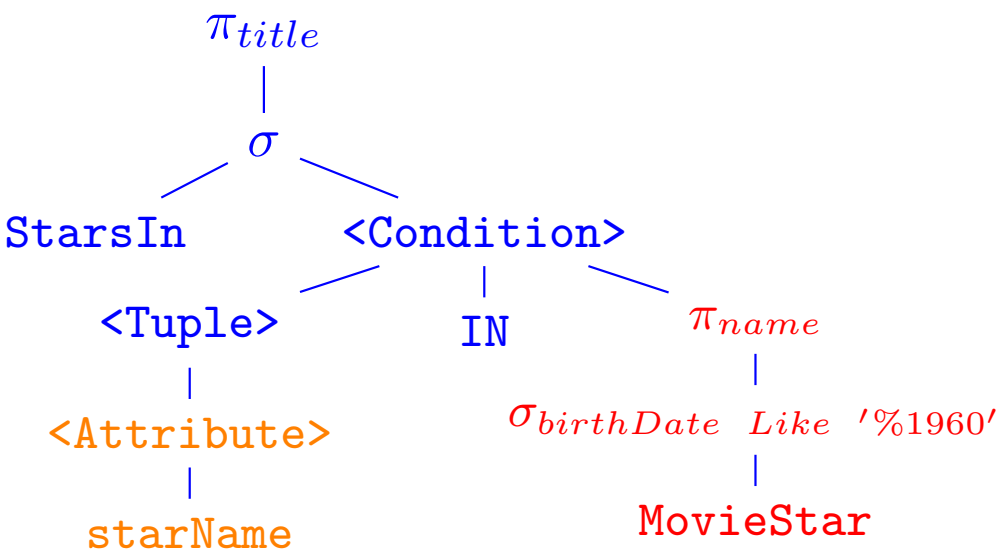


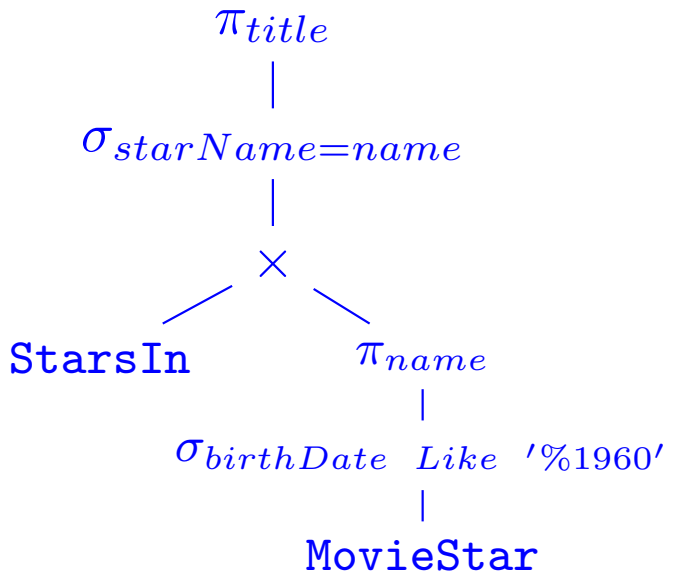
Conversion into Relational Algebra: Example 5(Cont.)

- Example (cont.):

```
SELECT title FROM StarsIn WHERE starName IN (...);
```

  - replace **<Condition>** with the tree representing the **sub-query**
  - replace the **two-argument selection** by a **one-argument selection** σ_C, where **C** is $starName = name$
  - give σ_C an argument that is the **product** of **StarsIn** and **MovieStar**





Conversion into Relational Algebra

- Translating sub-queries can be more complex if the sub-query is correlated to values defined outside its scope
  - we must produce a relation with some extra attributes for comparison with external attributes
  - the extra attributes are later removed using projections
  - any duplicate tuples must be removed
- Translating the parse tree into expressions in algebra may give several equivalent LQP using different operators or just changing the order of the operators

Summary

- SQL text $\rightarrow$ Internal representation
- Semantic checks
- View unfolding
- Conversion into Relational Algebra

Next

- When we have translated the parse tree to a relational algebra expression, the next step is to optimize the expression