# Datenbanksysteme II: Query Execution

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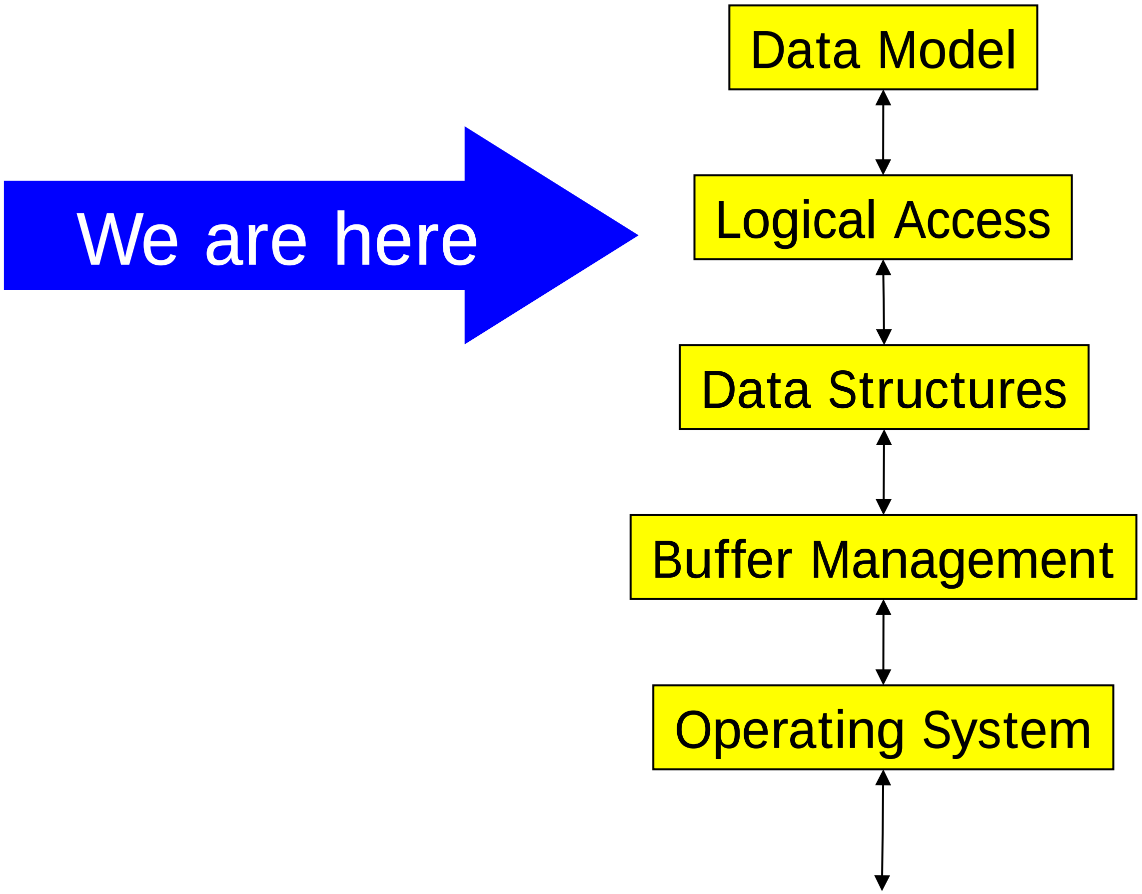
# Content of this Lecture

- Overview: Query optimization
- Relational operators
- Implementing (some) relational operators
- Query execution models

# 5 Layer Architecture



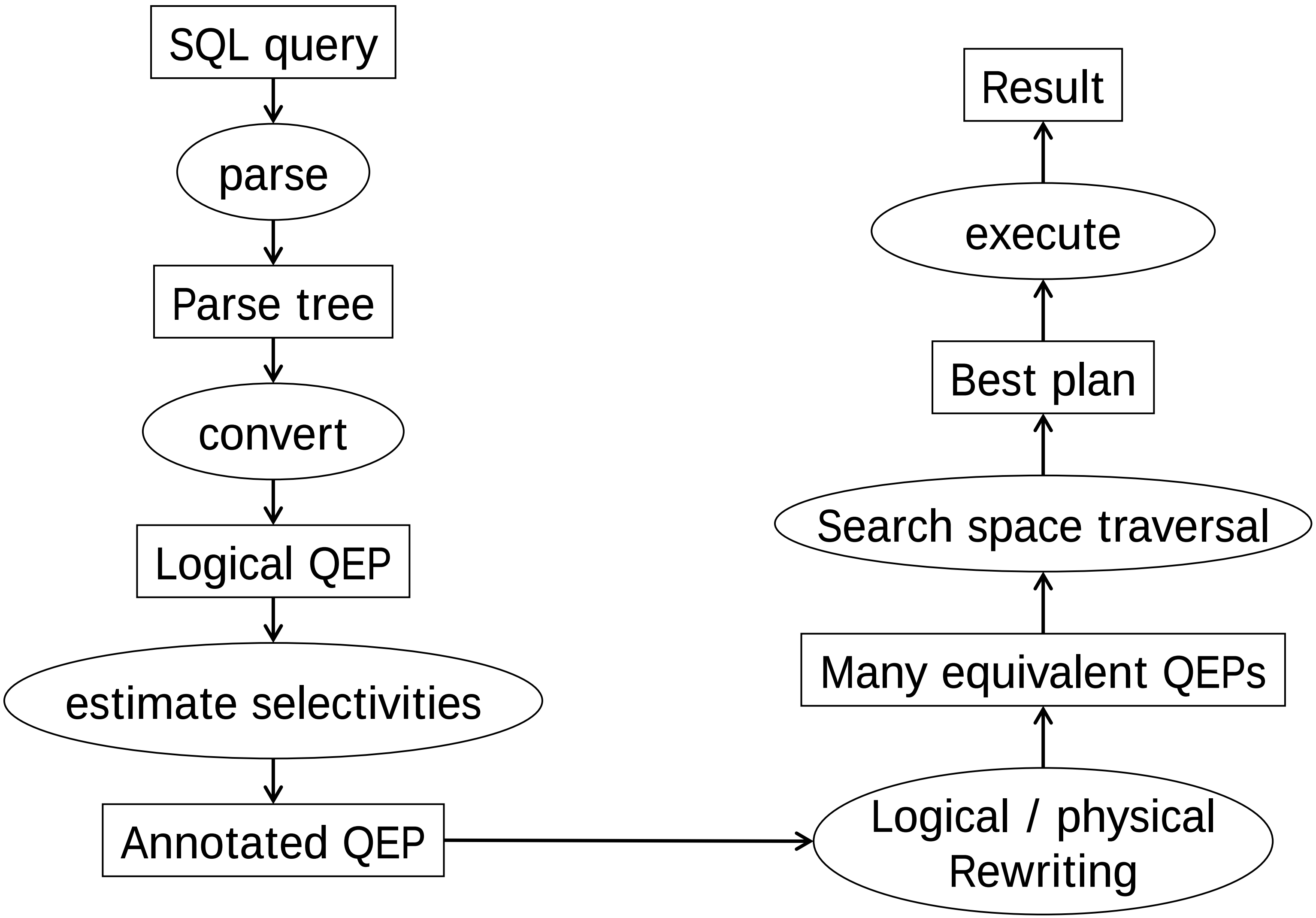
# Query Optimization

- We have
  - Structured Query Language SQL
  - Relational algebra
  - How to access tuples in many ways (scan, index, ...)
- Now
  - Given a SQL query
  - Find a fast way and order of accessing tuples from different tables such that the answer to the query is computed
  - Usually, we won't find the best way, but avoid the worst
  - Use knowledge about value distributions, access paths, query operators, IO cost, ...
  - Compile a declarative query in an "optimal" executable program

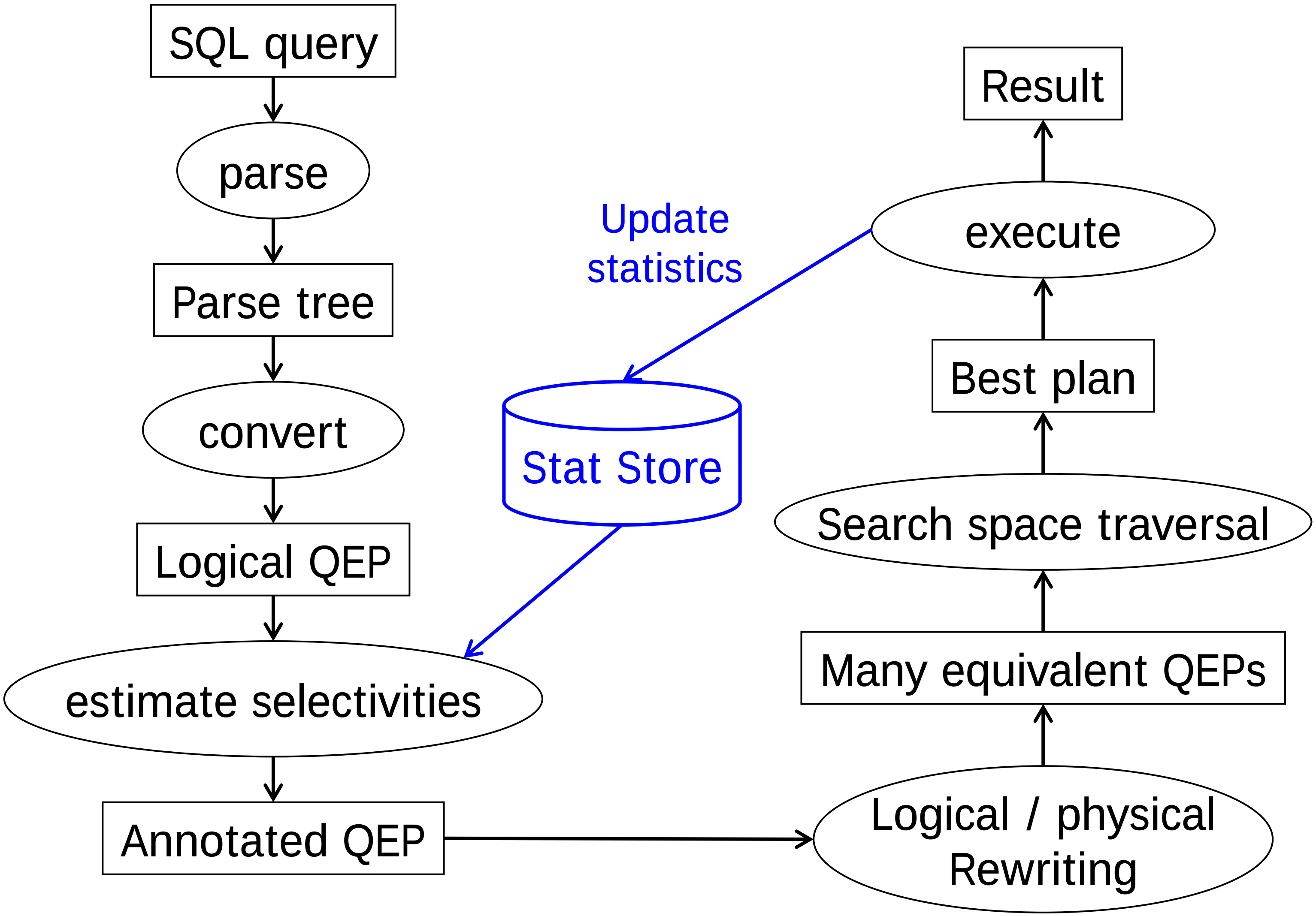
# Steps (Sketch)

- Translate query in a logical query execution plan (QEP)
  - Structured representation of a relational algebra expression
- Logical optimization: QEPs are rewritten in other, semantically equivalent and hopefully faster QEPs
  - E.g., selection is commutative: $\sigma_A(\sigma_B(expr)) = \sigma_B(\sigma_A(expr))$
- Physical optimization: For each (relational) operator in the query, we have multiple possible implementations
  - Table access: scan, indexes, sorted access through index, ...
  - Joins: Nested loop, sort-merge, hash, ...
- Query execution: Execute the best query plan found

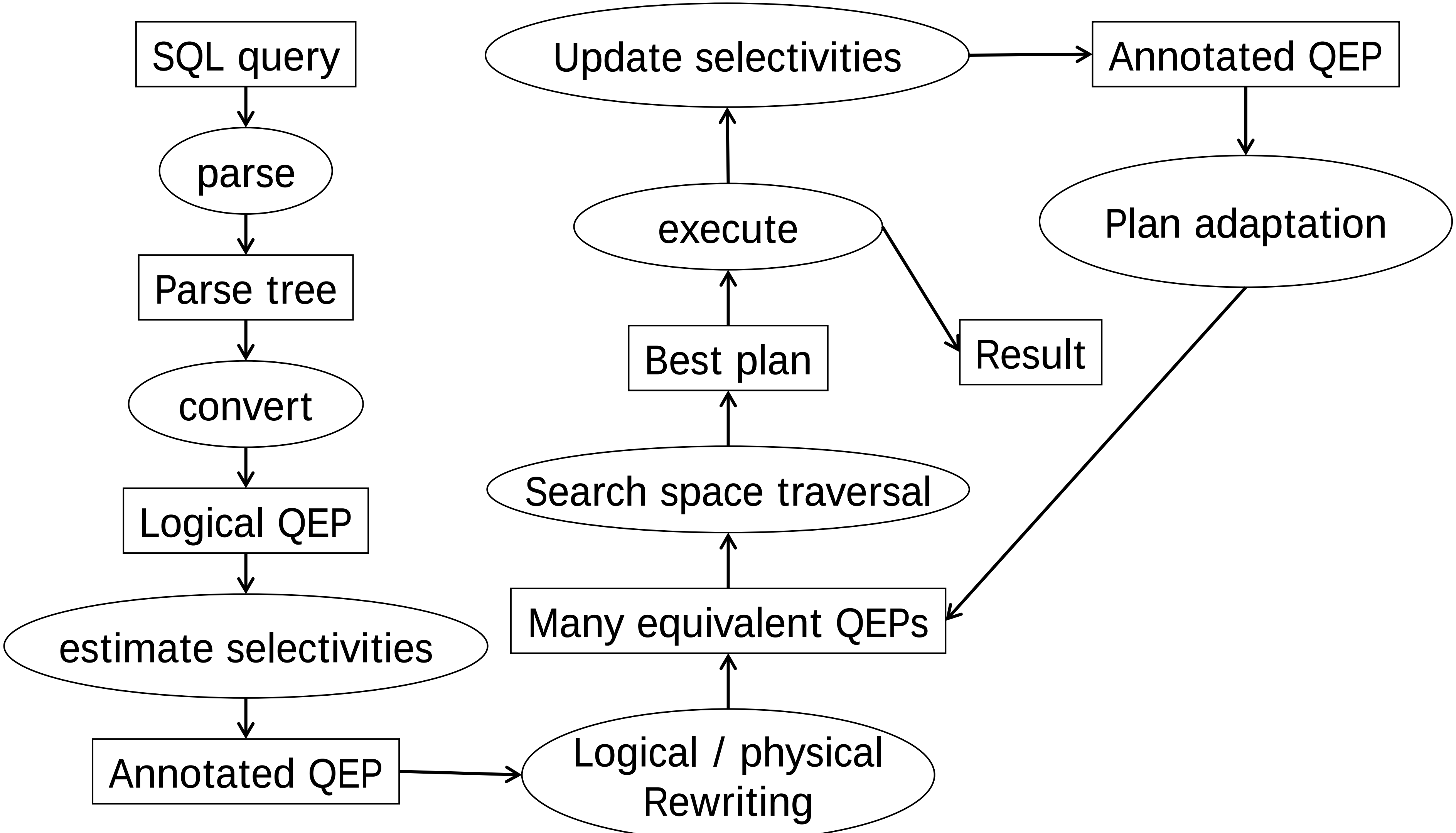
# Overview Optimization



# Overview Optimization



# Adaptive Optimization



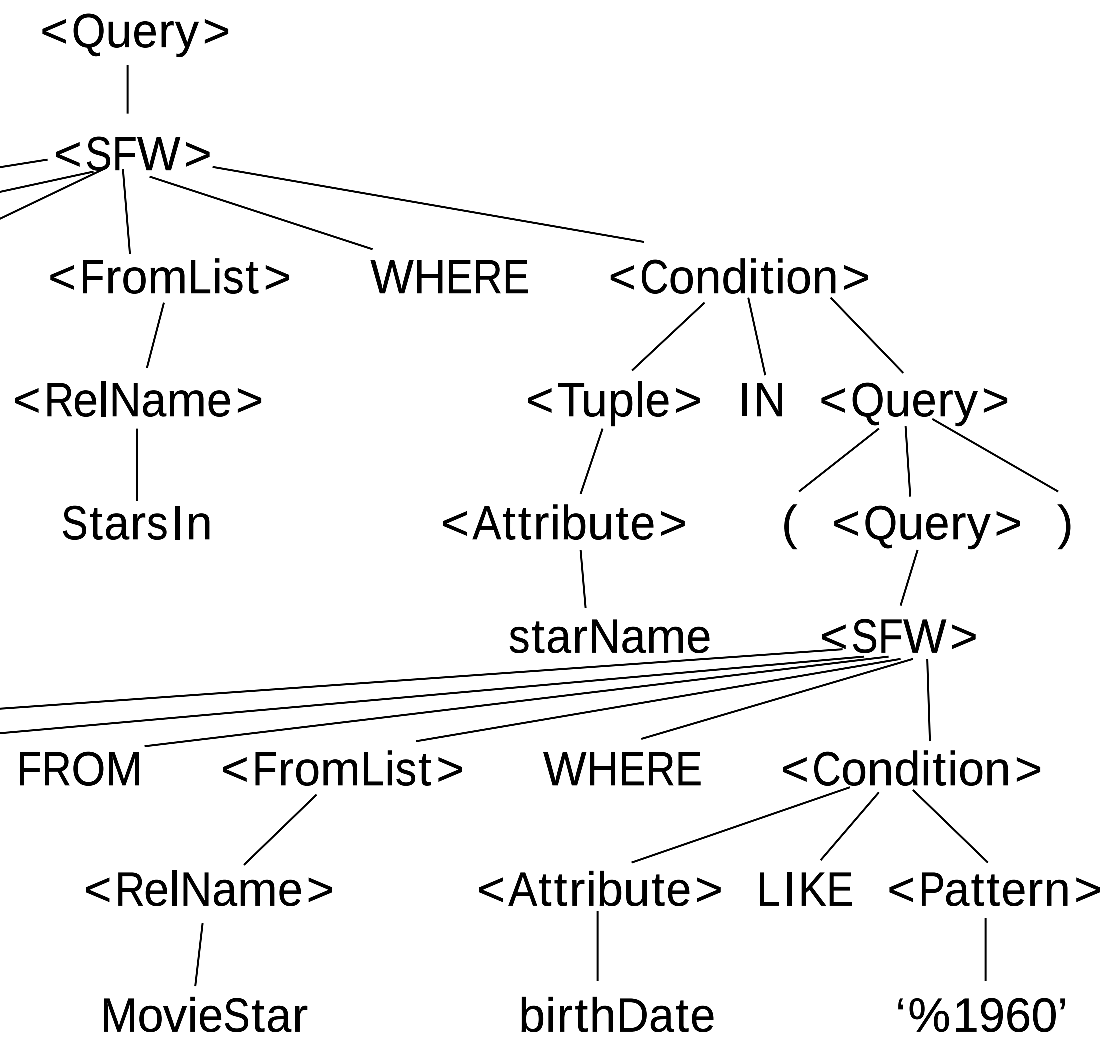
# Example SQL query

```
SELECT title
FROM   starsIn
WHERE  starName IN (
         SELECT name
         FROM movieStar
         WHERE birthdate LIKE ‘%1960’
       );
```

(Find all movies with stars born in 1960)

# Parse Tree

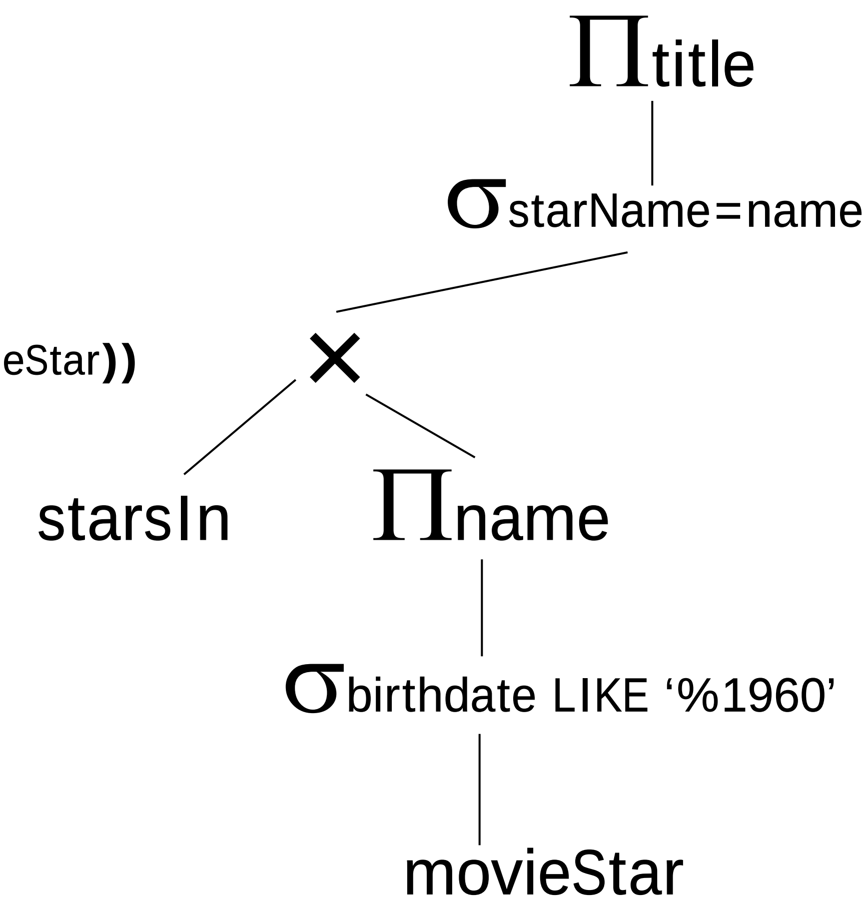
```
SELECT title
FROM   starsIn
WHERE  starName IN (
 SELECT name
 FROM movieStar
 WHERE birthdate LIKE ‘%1960’
);
```



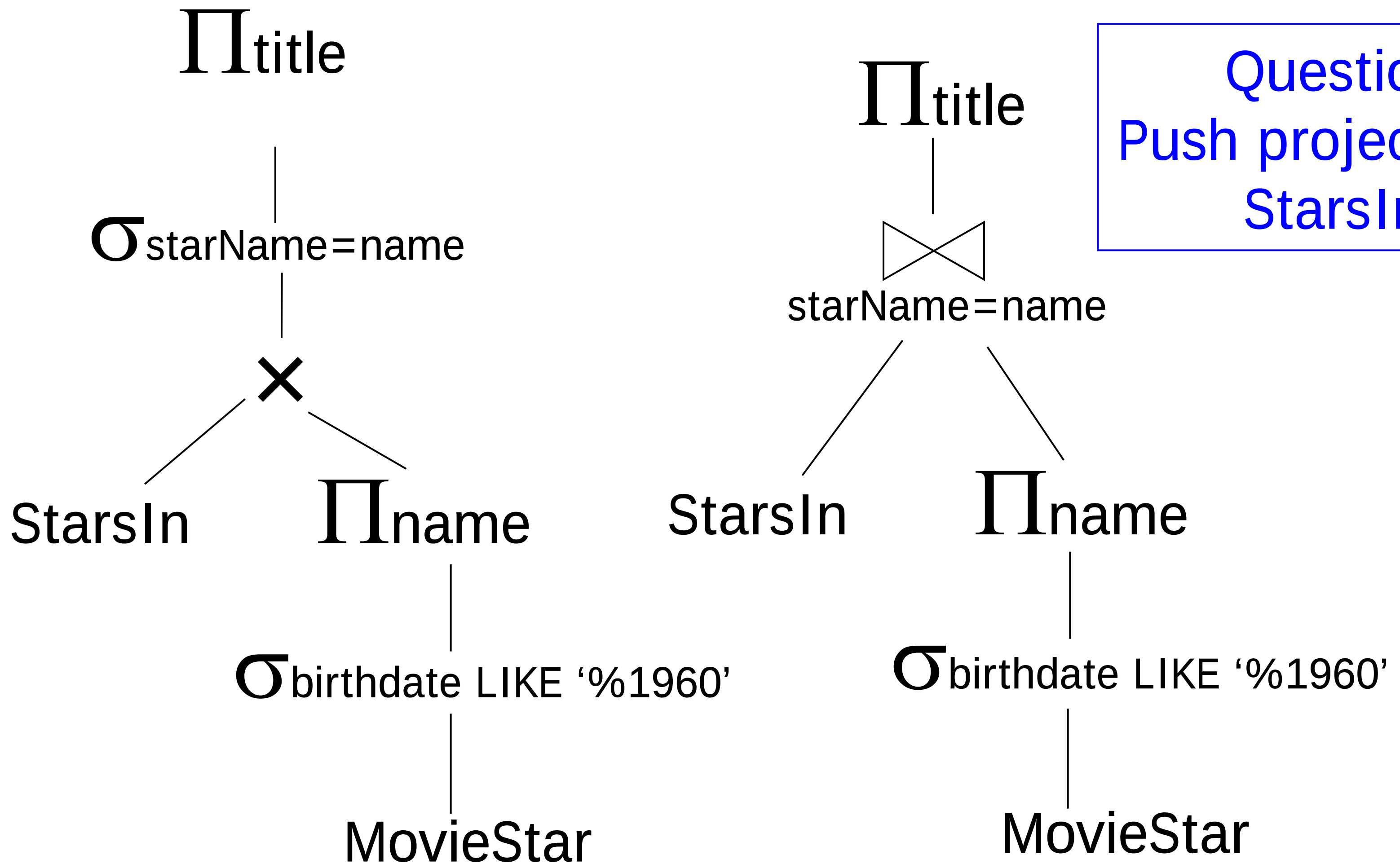
# Relational Algebra / Logical Query Plan

```
SELECT title
FROM   starsIn
WHERE  starName IN (
 SELECT name
 FROM movieStar
 WHERE birthdate LIKE ‘%1960’
);
```

$\Pi_{\textbf{title}}\ (\sigma_{\textbf{starName=name}}(\text{starsIn}) \times \sigma_{\textbf{birthdate}}(\text{movieStar}))$

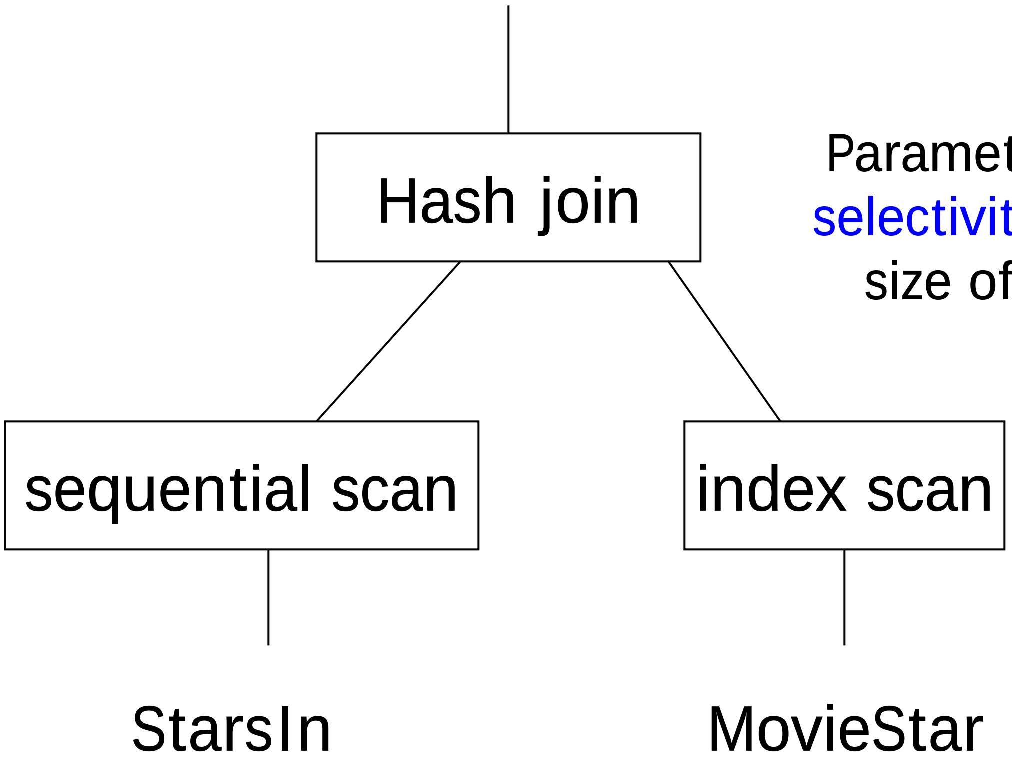


# Improved Logical Query Plan




Question:
Push projection to StarsIn?

# Physical Plan




Parameters: Join order, selectivity, memory size, size of attributes, ...

Parameters: Selectivity, fragmentation of data file, size of tuples, ,...

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# Relational Operations: One Table

- In the following: Table means table or intermediate result
- Selection $\sigma$: WHERE clause
  - Read table and filter tuples based on condition
  - Possibility: Use index to access only the qualifying tuples
  - Selection never increases table length (selectivity)
  - Conjunctions, disjunction, equality, negation, ...
- Projection $\pi$: SELECT clause
  - Read table and manipulate columns
  - In SET semantic, also duplicates must be filtered
  - Projection usually decreases breadth of table
    - When not?

# Relational Operations: One Table cont'd

- Group-by: Grouping and aggregation
  - Put all tuples with equal values in all grouping attributes into one bag; output one tuple per bag by aggregating values
  - Implementation by sorting or hashing
- Distinct: Duplicate elimination
  - Read table and remove all duplicate tuples
  - May also be injected to speed-up EXIST clauses
  - Implementation by sorting or hashing
- Order-by: Sorting
  - Always last clause in query, but injected often by optimizer
  - Pipeline breaker

# Relational Operations: Two Tables

- Cartesian product x
  - Read two tables and build all pairs of tuples
  - Usually avoided – combine product and selection to join
  - Products in a plan are hints to wrong queries
  - Specified implicitly by FROM clause
- Join ⋈
  - All pairs of tuple matching the join condition
  - Natural join, theta join, equi join, semi join, outer join
  - Expensive – favorite target of optimizers
  - Possibility: Join-order and join implementation
  - Specified implicitly or explicitly in WHERE clause

# Relational Operations: Two Queries

- Union $\cup$
  - Read two tables and build union of all tuples
  - Duplicates are removed (alternative: UNION-ALL)
  - Requires tables to have same schema
- Intersection $\cap$
  - Read two tables and build intersection of tuples
  - Requires tables to have same schema
  - Same as join over all attributes
- Minus $/$
  - Subtract tuples of one table from tuples from the other
  - Requires tables to have same schema

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# Select versus Update

- We do not discuss update, delete, insert
- Update and delete usually have embedded queries – "normal" optimization
  - But: data tuples must be loaded (and locked and changed and persistently written if TX not rolled-back)
  - Some tricks don't work any more
- Insert may have query

# Implementing Operations

- Most single table operations are straight-forward
  - See book by Garcia-Molina, Ullmann, Widom for detailed discussion
- Joins are more complicated – later
- Sorting, especially for large tables, is important
  - External sorting – we have seen Merge-Sort
- We sketch three single table operations
  - Scanning a table
  - Duplicate elimination
  - Group By

# Scanning a Table

- At the bottom of each operator tree are relations
- Accessing them implies a table scan
  - If table T has b blocks, this costs b IO
- Often better: Combine with next operation in plan
  - `SELECT t.A, t.B FROM t WHERE A=5`
  - Selection: If index on T.A available, perform index scan
    - Assume |T|=n, |A|=a different values, z=n/a tuples with T.A=a
      - Index has height $\log_k(n)$
      - Scan B+ index and find all matching TIDs
      - Accessing z tuples from T costs 1-z IO (sequential or random)
    - Especially effective if A is a key: Only one tuple selected
  - Projection: Integrate into table scan
    - Read complete tuples, but only pass-on attributes that are needed
      - Why not read partial tuples?

# Scanning a Table 2

- Conditions can be complex

```
SELECT t.A, t.B FROM t
WHERE A=5 AND (B<4 OR B>9) AND C='müller' …
```

- Approach
  - Compute conjunctive normal form
  - Independent indexes: Find TID lists for each conjunct, then intersect
  - With MDIS: Directly find matching TIDs
  - Without indexes: Scan table and evaluate condition for each tuple
- For complex conditions and small tables, linear scanning usually is faster
  - Depends on expected result size
  - Cost-based optimization required

# Duplicate Elimination

- Option 1: Sorting
- Sort table on DISTINCT columns
  - Can be skipped if table is already sorted
- Scan sorted table and output only unique tuples
- Generates output in sorted order (for later reuse)
- Pipeline breaker (see later)
- Memory: Use external sorting, then pipeline

# Duplicate Elimination

- Option 2: Use hashing
- Scan table and build hash table on all unique values
  - Needs good hash function, avoid conflicts
- When reading a tuple, check if it has already been seen
  - If not: insert tuple and copy it to the output; else: skip tuple
  - No pipeline breaker
  - Does not sort result (but existing sorting would remain)
- No pipeline breaker
- Memory: Problem; assumes S to fit in memory

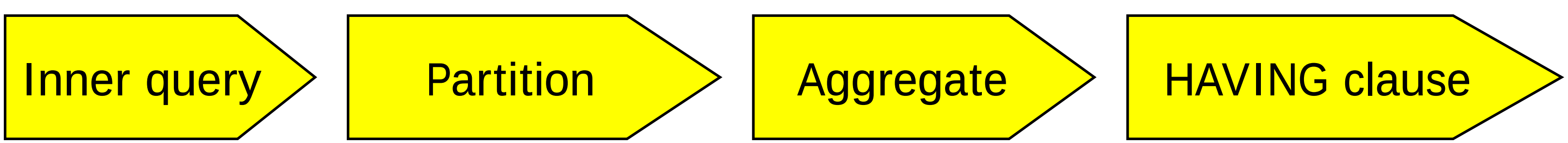
# Performance

- Assumptions
  - Main memory: m blocks
  - Table: b blocks
- Using external sorting
  - If table is sorted, we need b IO
  - If table not sorted, we need $2*b*\text{ceiling}(\log_m(b))-b$ IO
- Using internal data structure
  - If all distinct values fit into m, we need b IO
    - Estimate from statistics
  - Otherwise ... use two pass algorithms (e.g. hash-join like; later)

# Grouping and Aggregation

```
SELECT T.day_id, sum(amount*price)
FROM   sales S
GROUP  BY T.day_id
```

- SELECT must contain only GROUP BY attributes and aggregate functions
- Partition result of inner query by GROUP BY attributes
- For each partition, compute one result tuple: GROUP BY attributes and aggregate function applied on values of other attributes in this partition
  - Note: Depending on the aggregate function, we might need to buffer more than one value per partition – examples?



# Implementing GROUP BY

- Proceed like duplicate elimination
- Also keep to-be-aggregated attributes
- Eventually, compute the aggregated columns
  - Simple: SUM, COUNT, MIN, MAX, ANY
  - More memory required: AVG, Top-5, median
- Pipelining? Same properties as for duplicate elimination

# Computing Median

- Option 1: Partition table into k partitions
  - Scan table
  - Build (hash) table for first k different GROUP BY values
  - When reading one of first k, add value to (sorted) list
  - When reading other GROUP value, discard
  - When scan finished, output median of k groups
  - Iterate – next k groups
- Option 2: Sort table on GROUP BY and Median attribute
  - Then scan sorted data
  - Buffer all values per group
  - When next group is reached, output middle value
- What if we cannot buffer all values of a group?

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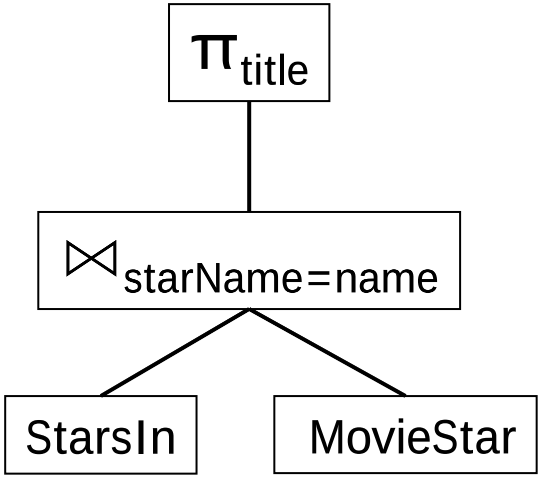
# Query Execution

- Typical model: Operator implementations call each other to pass tuples up the tree
  - Iterator concept: Open, next, close
    - Each operator implementation needs these three methods
  - Produces deep stacks and many push/pops
  - Plan generation is simple: Composition of independent blocks
- Two modes: Blocked, Pipelined
- Work mostly done in open (if blocking) or in next (if pipelined)

- Modern alternative: Compile into function-free program

# Example – Blocked (Sketch

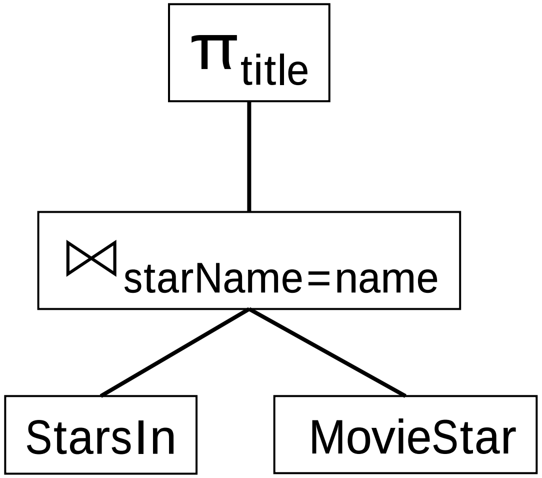
```
p = projection.open();
while p.next(t)
    output t;
p.close();
```




```
class projection {
open() {
  j = join.open();
  while j.next(t)
    tmp[i++]=t.title;
  j.close();
  cnt:=0;
}
next( t) {
  if (cnt<tmp.max)
    t = tmp[cnt++];
    return true;
  else return false;
}
close() {
  discard( tmp);
}
}
```

```
class join {
open() {
  l = table.open(starsIn);
  while l.next(tl)
    r = table.open(movieStar)
    while r.next(tr)
      if tl.starname=tr.name
        tmp[i++]=tl⋈tr;
    r.close();
  end while;
  l.close();
  cnt:=0;
}
next( t) {
 if (cnt<tmp.max)
    t = tmp[cnt++];
    return true;
  else return false;
}
close() {
  discard( tmp);
```

# Example – Pipelined (Sketch)

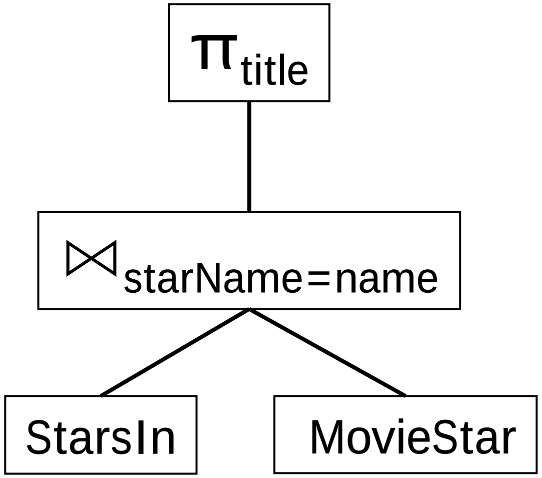



```
p = projection.open();
while p.next(t)
    output t;
p.close();
```

```
class projection {
open() {
  j = join.open();
}
next(t) {
  if j.next( t)
    return t.title
  else
  return false;
}
close() {
  j.close();
}
}
```

```
class join {
open() {
  l = table.open(starsIn);
  r = table.open(movieStar);
  l.next( tl);
}
next( t) {
  if r.next(tr)
    if tl.starname=tr.name
      t=tl⋈tr;
     return true;
  else
    if l.next( tl)
      r.close();
      r = table.open(movieStar);
      return next( t);
    else
      return false;
}
close() {
  l.close();
  r.close();
```

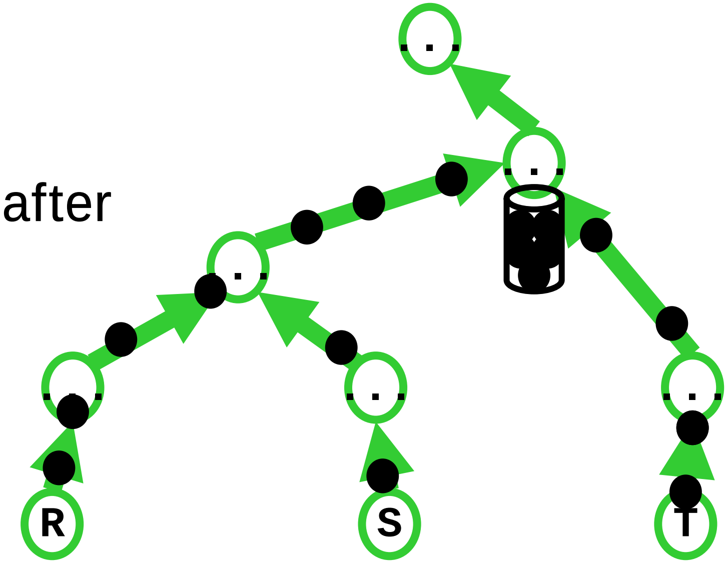
# Example – Compiled (Sketch)




```
l = table.open(starsIn);
r = table.open(movieStar);
go = l.next( tl);
while go do
  if r.next(tr)
    if tl.starname=tr.name
      t=tl⋈tr;
      output t.title;
  else
    if l.next( tl)
      r.close();
      r = table.open(movieStar);
    else
      l.close();
      r.close();
      go = false;
}
```

# Pipelined versus Blocked

- Pipelining is in general advantageous
  - Very little demand for buffer space
    - When intermediate results are large, buffers need to be stored on disk
  - Operations can be assigned to different threads or CPUs
    - Overlapping execution
  - Results come early and continuously
- Pipeline breaker
  - Some operations cannot be pipelined
  - Sorting: next() can be executed only after entire table was read
    - Exception: When input is sorted
  - Grouping and aggregation
    - Depending on implementation
  - Minus, intersection



# Pipelined versus Blocked

- Projection with duplicate elimination
  - Need not be a pipeline breaker
  - Recall implementation without sorting
  - next() can return early
  - But we need to keep track of all values already returned – requires large buffer

# Bag and Set Semantic

- Relational algebra has SET semantic
  - All relations are duplicate-free
  - Result of each query is duplicate-free
  - Result of each intermediate result is duplicate-free
- SQL databases use BAG semantic
  - More practical in applications
  - PKs are used to prevent existence of “real” duplicates
- But: Duplicate elimination remains an important task
  - Explicit DISTINCT clause
  - EXIST
  - ..