Query Execution + Retrospective

CREATING THE NEXT®

Administrivia

- Assignment 4 and Sheet 4 due on Dec 3.
- Project presentations on Dec 1 and Dec 6.
- Report due on Dec 6.

Today's Agenda

Query Execution (Part 1)

1.1 Recap

1.2 Processing Models

1.3 Access Methods

1.4 Expression Evaluation

1.5 Retrospective

Recap

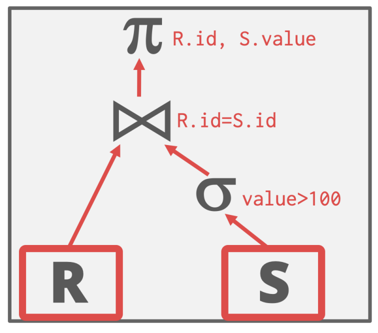
Join Algorithms: Summary

Join Algorithm	IO Cost	Example
Simple Nested Loop Join	M + (m x N)	1.3 hours
Block Nested Loop Join	M + (M x N)	50 seconds
Index Nested Loop Join	M + (M x C)	Variable
Sort-Merge Join	M + N + (sort cost)	0.75 seconds
Hash Join	3 x (M + N)	0.45 seconds

Query Plan

- The operators are arranged in a tree.
- Data flows from the leaves of the tree up towards the root.
- The output of the root node is the result of the query.

```
SELECT R.id, S.cdate
  FROM R, S
  WHERE R.id = S.id AND S.value > 100
```



Processing Models

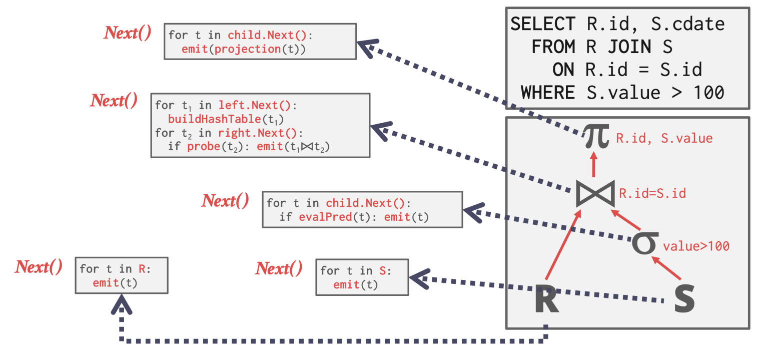
Processing Model

- A DBMS's **processing model** defines how the system executes a query plan.
  - Different trade-offs for different workloads.
- **Approach 1:** Iterator Model
- **Approach 2:** Materialization Model
- **Approach 3:** Vectorized / Batch Model

Iterator Model

- Each query plan operator implements a `Next` function.
  - On each invocation, the operator returns either a single tuple or a null marker if there are no more tuples.
  - The operator implements a loop that calls next on its children to retrieve their tuples and then process them.
- Also called **volcano** or **pipeline** model.

Iterator Model



```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```

Next()

```
for t in child.Next():
  emit(projection(t))
```

Next()

```
for t1 in left.Next():
  buildHashTable(t1)
for t2 in right.Next():
  if probe(t2): emit(t1⋈t2)
```

Next()

```
for t in child.Next():
  if evalPred(t): emit(t)
```

Next()

```
for t in R:
  emit(t)
```

Next()

```
for t in S:
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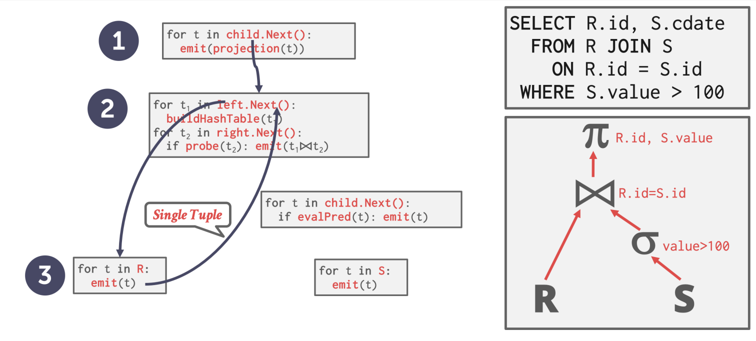
```

Iterator Model



1

```
for t in child.Next():
  emit(projection(t))
```

2

```
for t1 in left.Next():
  buildHashTable(t1)
for t2 in right.Next():
  if probe(t2): emit(t1⋈t2)
```

Single Tuple

```
for t in child.Next():
  if evalPred(t): emit(t)
```

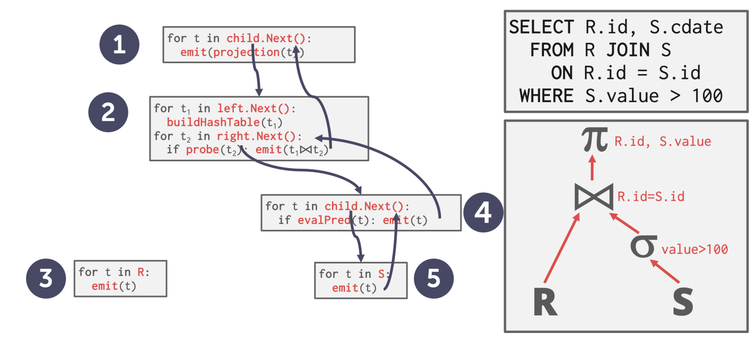
3

```
for t in R:
  emit(t)
```

```
for t in S:
  emit(t)
```

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```

Iterator Model



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```
for t in R:
  emit(t)
```

4
```
for t in child.Next():
  if evalPred(t): emit(t)
```

5
```
for t in S:
  emit(t)
```

```
SELECT R.id, S.cdate
  FROM R JOIN S
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 WHERE S.value > 100
```

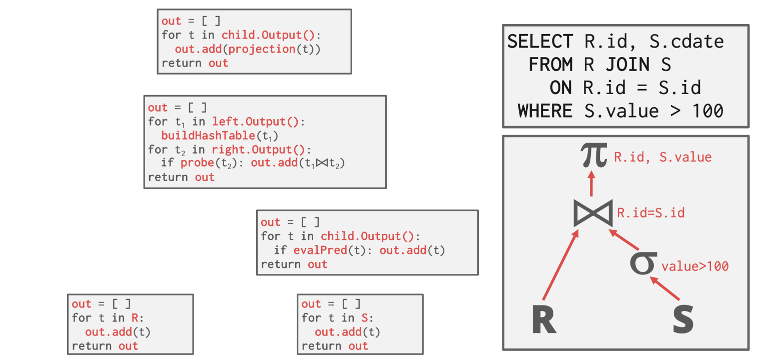
Iterator Model

- This is used in almost every DBMS. Allows for tuple **pipelining**.
- Some operators have to block until their children emit all of their tuples.
- These operators are known as **pipeline breakers**
  - Joins, Subqueries, Order By
- Output control (*e.g.*, `LIMIT`) works easily with this approach.
- **Examples:** SQLite, MySQL, PostgreSQL

Materialization Model

- Each operator processes its input **all at once** and then emits its output all at once.
  - The operator "materializes" its output as a single result.
  - The DBMS can push down **hints** into to avoid scanning too many tuples (*e.g.*, `LIMIT`).
  - Can send either a materialized row or a single column.
- The output can be either whole tuples (NSM) or subsets of columns (DSM)

Materialization Model



```
out = [ ]
for t in child.Output():
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return out
```

```
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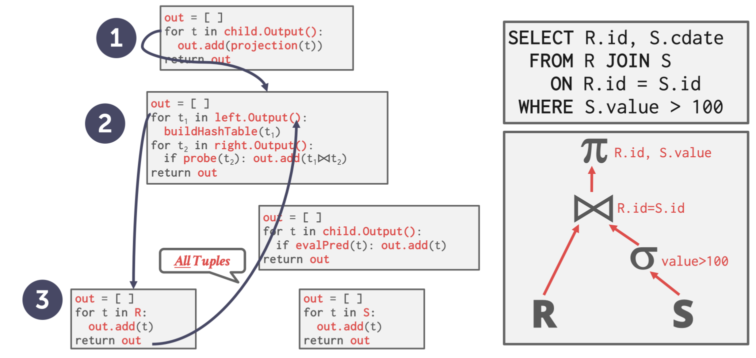

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```
out = [ ]
for t in S:
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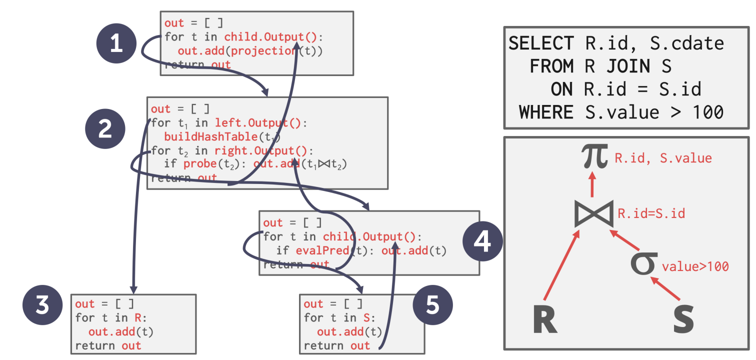
Materialization Model



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```
SELECT R.id, S.cdate
  FROM R JOIN S
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 WHERE S.value > 100
```

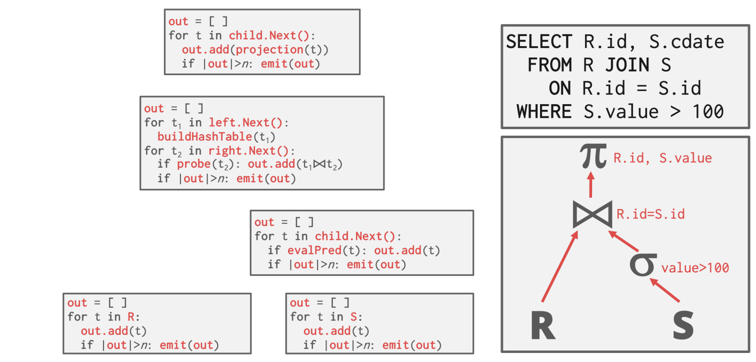
Materialization Model

- Better for OLTP workloads because queries only access a small number of tuples at a time.
  - Lower execution / coordination overhead.
  - Fewer function calls.
- Not good for OLAP queries with large intermediate results.
- **Examples:** MonetDB, VoltDB

Vectorization Model

- Like the Iterator Model where each operator implements a Next function in this model.
- Each operator emits a **batch of tuples** instead of a single tuple.
  - The operator's internal loop processes multiple tuples at a time.
  - The size of the batch can vary based on hardware or query properties.
  - Useful in in-memory DBMSs (due to fewer function calls)
  - Useful in disk-centric DBMSs (due to fewer IO operations)

Vectorization Model



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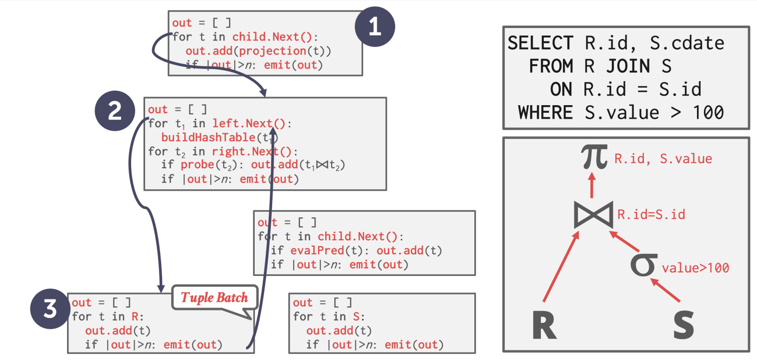
Vectorization Model



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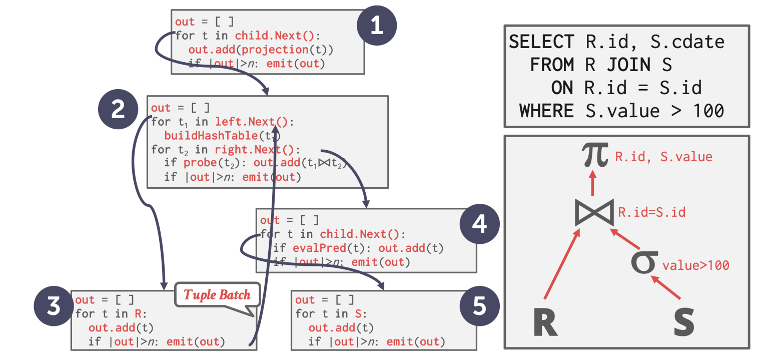
Vectorization Model



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SELECT R.id, S.cdate
  FROM R JOIN S
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 WHERE S.value > 100
```

Vectorization Model

- Ideal for OLAP queries because it greatly reduces the number of invocations per operator.
- Allows for operators to use vectorized (SIMD) instructions to process batches of tuples.
- **Examples:** Vectorwise, Snowflake, SQL Server, Oracle, Amazon RedShift

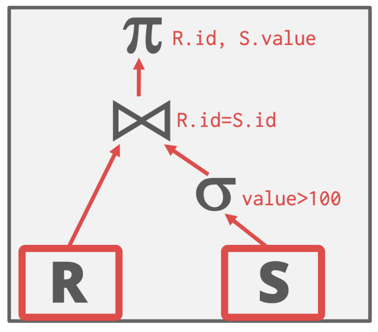
Plan Processing Direction

- **Approach 1: Top-to-Bottom**
  - Start with the root and "pull" data up from its children.
  - Tuples are always passed with function calls.
- **Approach 2: Bottom-to-Top**
  - Start with leaf nodes and push data to their parents.
  - Allows for tighter control of caches/registers in pipelines.

Access Methods

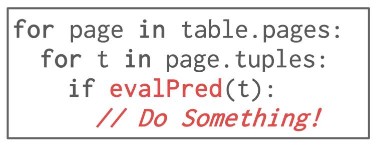
Access Methods

- An **access method** is a way that the DBMS can access the data stored in a table.
  - Located at the bottom of the query plan
  - Not defined in relational algebra.
- Three basic approaches:
  - Sequential Scan
  - Index Scan
  - Multi-Index / "Bitmap" Scan



Sequential Scan

- For each page in the table:
  - Retrieve it from the buffer pool.
  - Iterate over each tuple and check whether to include it.
  - Uses a buffer for materialization and vectorization processing models
- The DBMS maintains an internal **cursor** that tracks the last page / slot it examined.



```
for page in table.pages:
  for t in page.tuples:
    if evalPred(t):
      // Do Something!
```

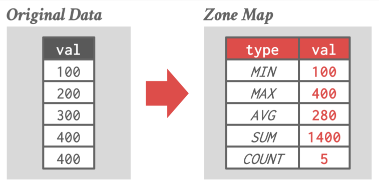
Sequential Scan: Optimizations

- This is almost always the worst thing that the DBMS can do to execute a query.
- Sequential Scan Optimizations:
  - Prefetching
  - Buffer Pool Bypass
  - Parallelization
  - Zone Maps
  - Late Materialization
  - Heap Clustering

Zone Maps

- Pre-computed aggregates for the attribute values in a page.
- DBMS checks the zone map first to decide whether it wants to access the page.

```
SELECT *
  FROM R
  WHERE val > 600
```



Original Data

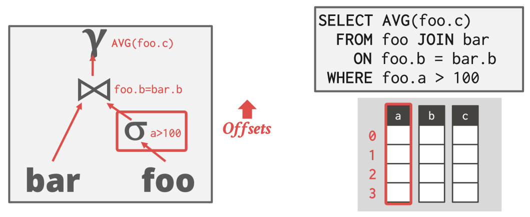
val
100
200
300
400
400

Zone Map

type	val
MIN	100
MAX	400
AVG	280
SUM	1400
COUNT	5

Late Materialization

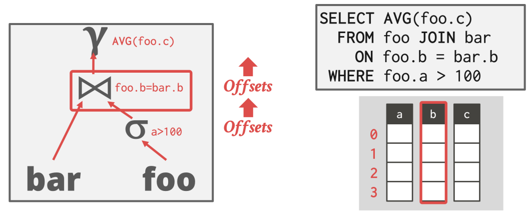
- DSM DBMSs can delay stitching together tuples until the upper parts of the query plan.



```
SELECT AVG(foo.c)
  FROM foo JOIN bar
    ON foo.b = bar.b
 WHERE foo.a > 100
```

Late Materialization

- DSM DBMSs can delay stitching together tuples until the upper parts of the query plan.



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Late Materialization

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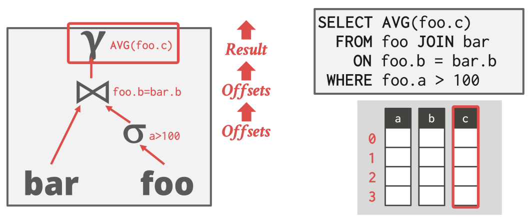

```
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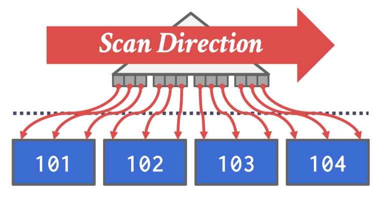
  FROM foo JOIN bar
    ON foo.b = bar.b
 WHERE foo.a > 100
```

Heap Clustering

- Tuples are sorted in the heap's pages based on the order specified by the clustering index.
- If the query accesses tuples using the clustering index's attributes, then the DBMS can jump directly to the pages that it needs.



Index Scan

- The **query optimizer** picks an index to find the tuples that the query needs.
- Which index to use depends on:
  - What attributes the index contains
  - What attributes the query references
  - The attribute's value domains
  - Predicate composition
  - Whether the index has unique or non-unique keys

Index Scan

- Suppose that we a single table with 100 tuples and two indexes:
  - Index 1: age
  - Index 2: dept

```
SELECT *
  FROM students
  WHERE age < 30
          AND dept = 'CS'
          AND country = 'US'
```

  - Scenario 1: There are 99 people under the age of 30 but only 2 people in the CS department.
  - Scenario 2: There are 99 people in the CS department but only 2 people under the age of 30.

Multi-Index Scan

- If there are multiple indexes that the DBMS can use for a query:
  - Compute sets of record ids using each matching index.
  - Combine these sets based on the query's predicates (union vs. intersect).
  - Retrieve the records and apply any remaining predicates.
- Postgres calls this **Bitmap Scan**.

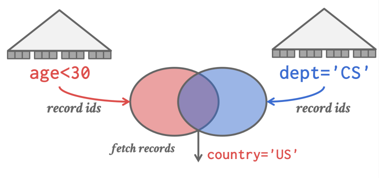
Multi-Index Scan

- With an index on age and an index on dept,
  - We can retrieve the record ids satisfying `age` < 30 using the first,
  - Then retrieve the record ids satisfying `dept` = 'CS' using the second,
  - Take their intersection
  - Retrieve records and check `country` = 'US'.

```
SELECT *
  FROM students
  WHERE age < 30
          AND dept = 'CS'
          AND country = 'US'
```

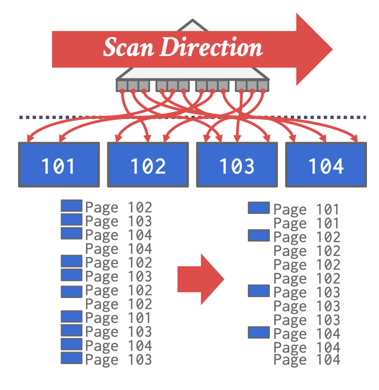
Multi-Index Scan

- Set intersection can be done with bitmaps, hash tables, or Bloom filters.



Index Scan Page Sorting

- Retrieving tuples in the order that appear in an **unclustered index** is inefficient.
- The DBMS can first figure out all the tuples that it needs and then sort them based on their page id.



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Expression Evaluation

Expression Evaluation

- The DBMS represents a WHERE clause as an **expression tree**.
- The nodes in the tree represent different expression types:
  - Comparisons (=, <, >, !=)
  - Conjunction (AND), Disjunction (OR)
  - Arithmetic Operators (+, -, *, /, %)
  - Constant Values
  - Tuple Attribute References

```
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  FROM R, S
  WHERE R.id = S.id
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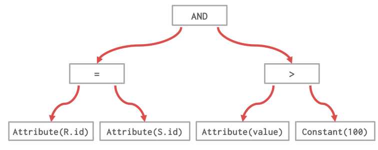
```



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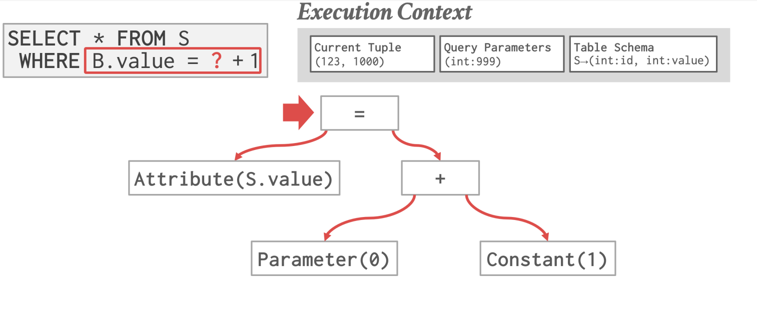


```
SELECT * FROM S
 WHERE B.value = ? + 1
```

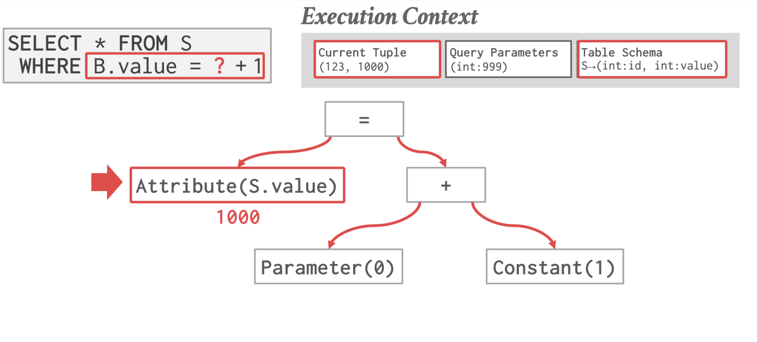
Execution Context

Current Tuple
(123, 1000)

Query Parameters
(int:999)

Table Schema
S→(int:id, int:value)

Expression Evaluation



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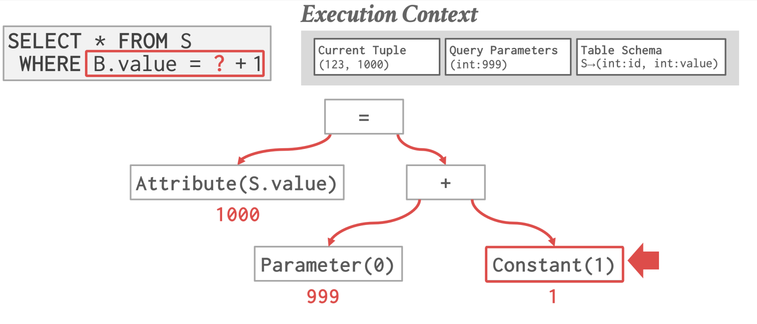
Expression Evaluation



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Execution Context

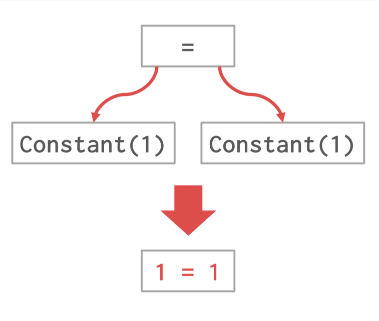
Current Tuple
(123, 1000)

Query Parameters
(int:999)

Table Schema
S→(int:id, int:value)

Expression Evaluation

- Evaluating predicates in this manner is slow.
  - The DBMS traverses the tree and for each node that it visits it must figure out what the operator needs to do.
- Consider the predicate "WHERE 1=1"
- A better approach is to just evaluate the expression directly.
  - Think Just-In-Time (JIT) compilation



Conclusion

- The same query plan be executed in multiple ways.
- (Most) DBMSs will want to use an index scan as much as possible.
- Expression trees are flexible but slow.

Retrospective

What did we learn

- You are tired of systems programming
- You are exhausted
- Let’s take a step back and think about what happened

Lessons learned

- Systems programming is hard
- Become a better programmer through the study of database systems internals
- Going forth, you should have a good understanding how systems work

Big Ideas

- Database systems are awesome – but are not magic.
- Elegant abstractions are magic.
- Declarativity enables usability and performance.
- Building systems software is more than hacking
- There are recurring motifs in systems programming.
- CS has an intellectual history and you can contribute.

What Next?

- We have barely scratched the surface. Follow-on course: CS 8803 (DBMS Implementation - Part II)
  - Query Optimization
  - Concurrency Control
  - Logging and Recovery Methods
  - Query Compilation + Vectorization
- Stay in touch
  - Tell me when this course helps you out with future courses (or jobs!)
  - Ask me cool DBMS questions

Parting Thoughts

- You have surmounted several challenges in this course.
- You make it all worthwhile.
- Please share your feedback via CIOS.