Intro to Database Systems (15-445/645)

12 Query Execution

Part 1

Carnegie Mellon University

FALL 2022

Andy Pavlo

ADMINISTRIVIA

Tuesday Oct 11th will be a pre-recorded lecture.

Homework #3 is due Sunday Oct 9th @ 11:59pm

Mid-Term Exam is **Thursday Oct 13th**
→ During regular class time @ 11:50-1:10pm

Project #2 is out now:
→ Info Q&A Session: **TONIGHT @ 8:00pm via Zoom**
→ Checkpoint #1: **Tuesday Oct 11th @ 11:59pm**
→ Checkpoint #2: **Wednesday Oct 26th @ 11:59pm**

PROJECTS

Do write your own tests.

Do practice defensive programming.

Do use a profiler to find performance problems.

Do not use Gradescope for debugging.

Do not directly email TAs for help.

Start Project #2! Do Not Wait! Trust me!

TODAY'S AGENDA

Processing Models
Access Methods
Modification Queries
Expression Evaluation
Mid-Term Review

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

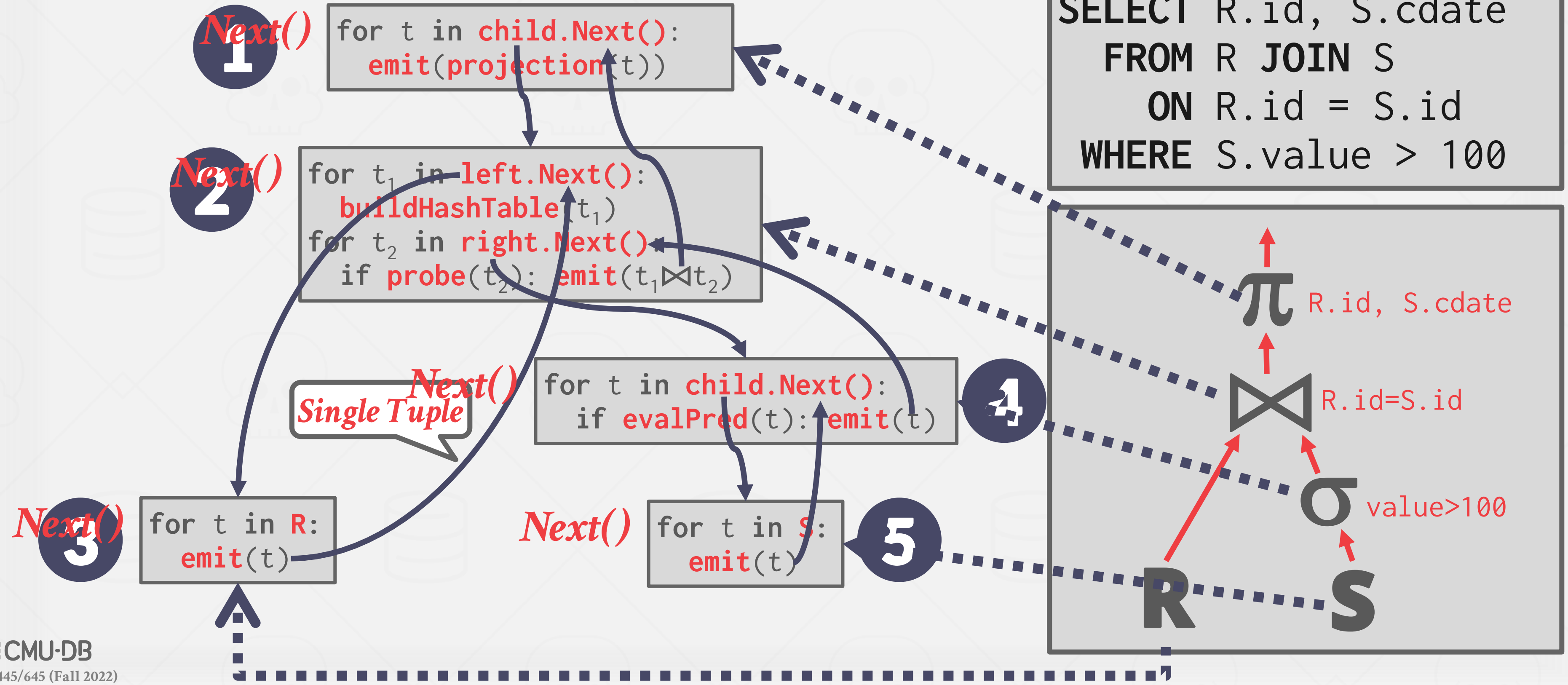
Each query plan operator implements a `Next()` function.

- → 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

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



ITERATOR MODEL

This is used in almost every DBMS. Allows for tuple pipelining.

Some operators must block until their children emit all their tuples.
→ Joins, Subqueries, Order By

Output control works easily with this approach.

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 (e.g., `LIMIT`) to avoid scanning too many tuples.
→ 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

1

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

2

```
out = [ ]
for t1 in left.Output():
  buildHashTable(t1)
for t2 in right.Output():
  if probe(t2): out.add(t1⋈t2)
return out
```

4

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

All Tuples

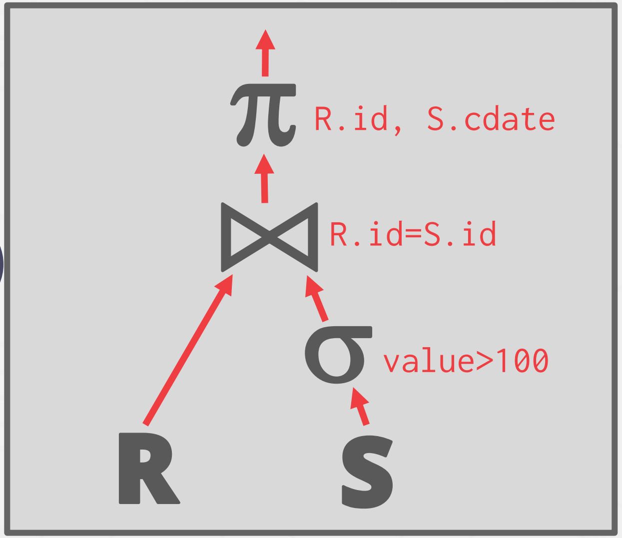
3

```
out = [ ]
for t in R:
  out.add(t)
return out
```

5

```
out = [ ]
for t in S:
  out.add(t)
return out
```

```sql
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 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.

VECTORIZATION MODEL

Like the Iterator Model where each operator implements a **Next()** function, but…

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.

VECTORIZATION MODEL

1
```
out = [ ]
for t in child.Next():
  out.add(projection(t))
  if |out|>n: emit(out)
```

2
```
out = [ ]
for t1 in left.Next():
  buildHashTable(t1)
for t2 in right.Next():
  if probe(t2): out.add(t1⋈t2)
  if |out|>n: emit(out)
```

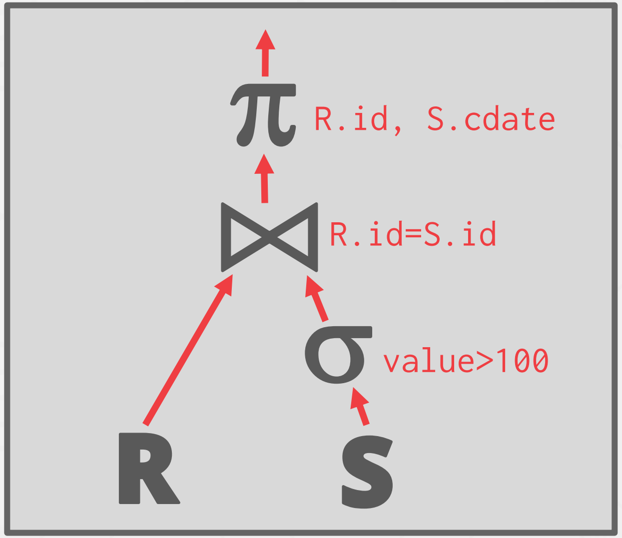
4
```
out = [ ]
for t in child.Next():
  if evalPred(t): out.add(t)
  if |out|>n: emit(out)
```

3
```
out = [ ]
for t in R:
  out.add(t)
  if |out|>n: emit(out)
```

Tuple Batch

5
```
out = [ ]
for t in S:
  out.add(t)
  if |out|>n: emit(out)
```

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



VECTORIZATION MODEL

Ideal for OLAP queries because it greatly reduces the number of invocations per operator.

Allows for operators to more easily use vectorized (SIMD) instructions to process batches of tuples.

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

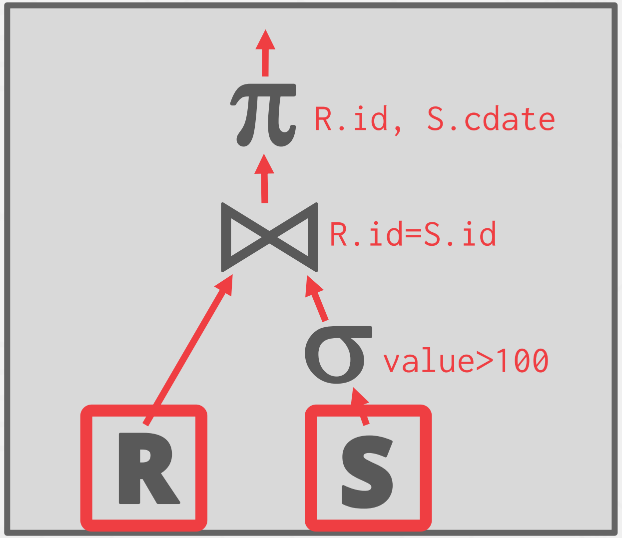
→ Start with leaf nodes and push data to their parents.
→ Allows for tighter control of caches/registers in pipelines.

ACCESS METHODS

An **access method** is the way that the DBMS accesses the data stored in a table.
→ Not defined in relational algebra.

Three basic approaches:
→ Sequential Scan
→ Index Scan (many variants)
→ Multi-Index Scan

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



SEQUENTIAL SCAN

For each page in the table:
- → Retrieve it from the buffer pool.
- → Iterate over each tuple and check whether to include it.

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

The DBMS maintains an internal **cursor** that tracks the last page / slot it examined.

SEQUENTIAL SCAN: OPTIMIZATIONS

This is almost always the worst thing that the DBMS can do to execute a query, but it may be the only choice available.

Sequential Scan Optimizations:

- Lecture #06 → Prefetching
- Lecture #06 → Buffer Pool Bypass
- Lecture #13 → Parallelization
- Lecture #08 → Heap Clustering
- Lecture #11 → Late Materialization
- → Data Skipping

DATA SKIPPING

Approach #1: Approximate Queries (Lossy)

- → Execute queries on a sampled subset of the entire table to produce approximate results.
- → Examples: BlinkDB, Redshift, ComputeDB, XDB, Oracle, Snowflake, Google BigQuery, DataBricks

Approach #2: Zone Maps (Loseless)

- → Pre-compute columnar aggregations per page that allow the DBMS to check whether queries need to access it.
- → Trade-off between page size vs. filter efficacy.
- → Examples: Oracle, Vertica, SingleStore, Netezza, Snowflake, Google BigQuery

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 table
 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

INDEX SCAN

The DBMS picks an index to find the tuples that the query needs.

Lecture #14

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

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

Suppose that we have a single table with 100 tuples and two indexes:

→ Index #1: **age**
→ Index #2: **dept**

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.

Examples:

→ DB2 Multi-Index Scan
→ PostgreSQL Bitmap Scan
→ MySQL Index Merge

MULTI-INDEX SCAN

With an index on **age** and an index on **dept**:

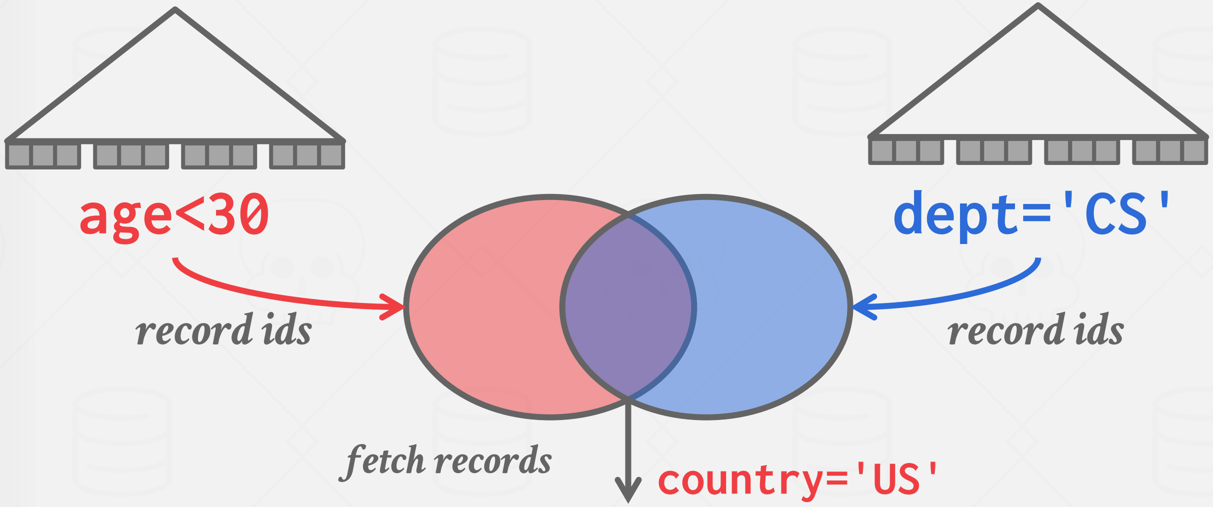
- → We can retrieve the Record IDs satisfying `age<30` using the first,
- → Then retrieve the Record IDs satisfying `dept='CS'` using the second,
- → Take their intersection
- → Retrieve records and check `country='US'`.

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

MULTI-INDEX SCAN

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

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



MODIFICATION QUERIES

Operators that modify the database (INSERT, UPDATE, DELETE) are responsible for modifying the target table and its indexes.

→ Constraint checks can either happen immediately inside of operator or deferred until later in query/transaction.

The output of these operators can either be Record Ids or tuple data (i.e., RETURNING).

MODIFICATION QUERIES

UPDATE/DELETE:

→ Child operators pass Record IDs for target tuples.
→ Must keep track of previously seen tuples.

INSERT:

→ **Choice #1**: Materialize tuples inside of the operator.
→ **Choice #2**: Operator inserts any tuple passed in from child operators.

UPDATE QUERY PROBLEM

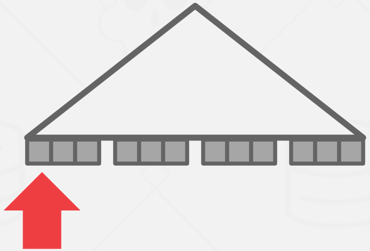
```
CREATE INDEX idx_salary
    ON people (salary);
```

```
UPDATE people
   SET salary = salary + 100
 WHERE salary < 1100
```

```
for t in child.Next():                    (1099,Andy)
  removeFromIndex(idx_salary, t.salary, t)
  updateTuple(t.salary = t.salary + 100)
  insertIntoIndex(idx_salary, t.salary, t)
```

```
for t in Index_people:
  if t.salary < 1100:
    emit(t)
```

Index(people.salary)



(999,Andy) (1099,Andy)

HALLOWEEN PROBLEM

Anomaly where an update operation changes the physical location of a tuple, which causes a scan operator to visit the tuple multiple times.

→ Can occur on clustered tables or index scans.

First discovered by IBM researchers while working on System R on Halloween day in 1976.

Solution: Track modified record ids per query.

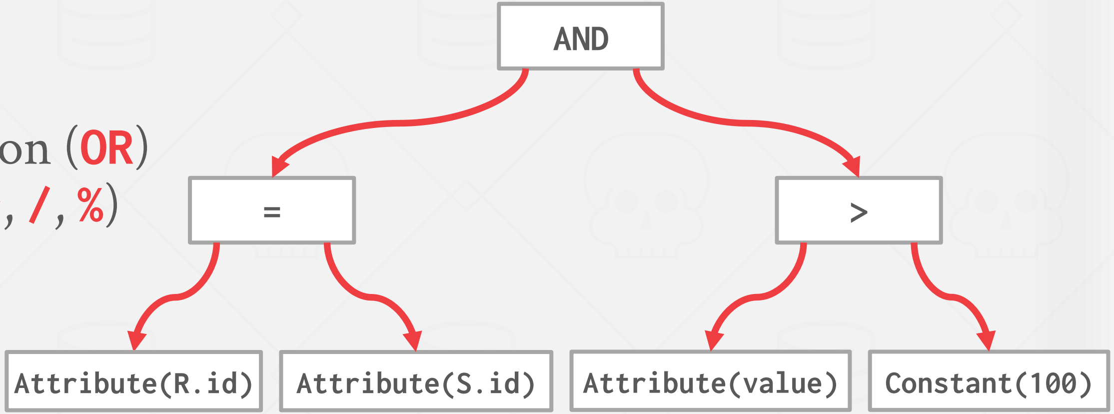
EXPRESSION EVALUATION

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

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



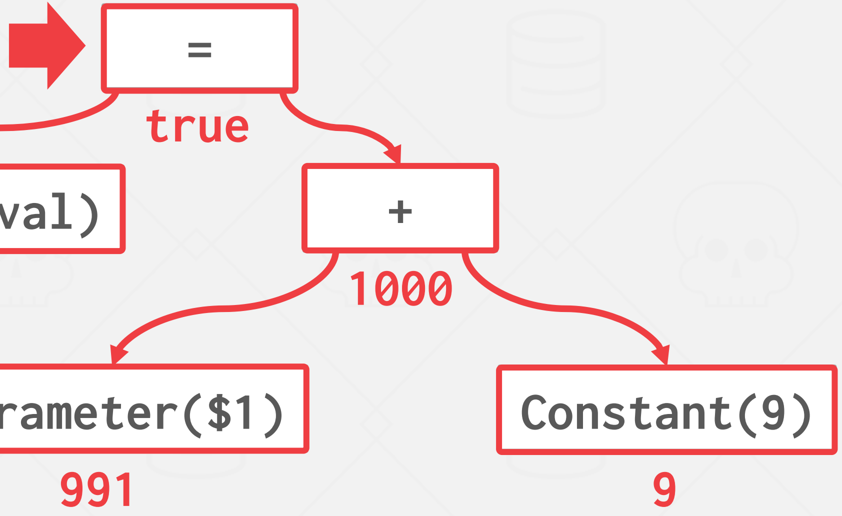
EXPRESSION EVALUATION

```
PREPARE xxx AS
  SELECT * FROM S
   WHERE S.val = $1 + 9
```

```
EXECUTE xxx(991)
```

Execution Context

Current Tuple	Query Parameters	Table Schema
(123, 1000)	(int:991)	S→(int:id, int:val)



EXPRESSION EVALUATION

Evaluating predicates in this manner is slow.

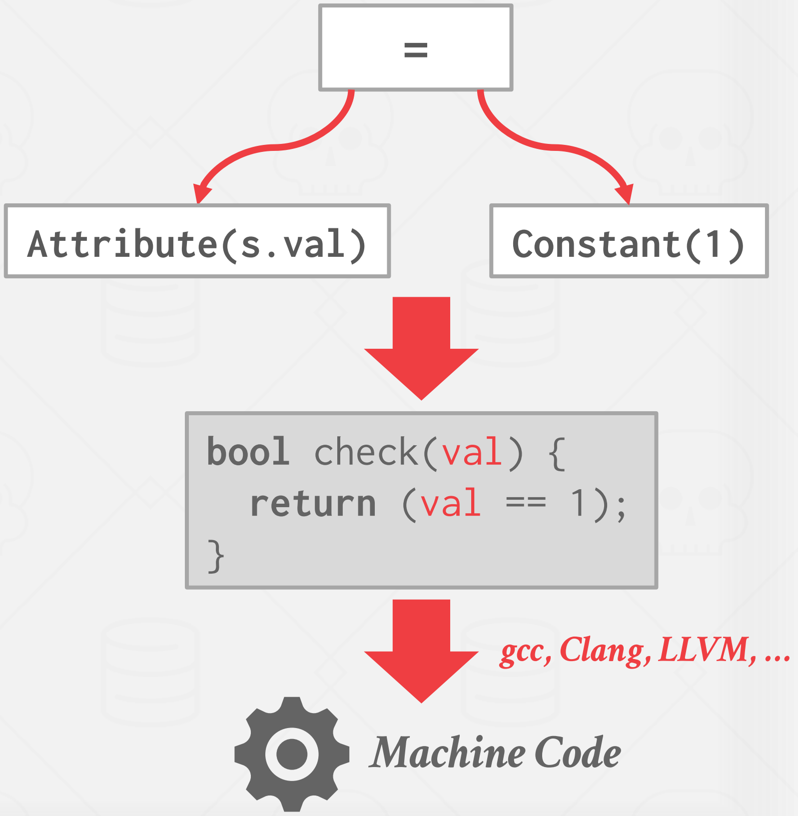
→ The DBMS traverses the tree and for each node that it visits it must figure out what the operator needs to do.

Consider this predicate:

`WHERE S.val=1`

A better approach is to just evaluate the expression directly.

→ Think JIT compilation



CONCLUSION

The same query plan can be executed in multiple different ways.

(Most) DBMSs will want to use index scans as much as possible.

Expression trees are flexible but slow.
JIT compilation can (sometimes) speed them up.

NEXT CLASS

Parallel Query Execution

MIDTERM EXAM

Who: You

What: Midterm Exam

Where: Tepper 1403

When: Thursday Oct 16th @ 11:50am-1:10pm

Why: https://youtu.be/CLe-TtmNuug

Email Andy if you need special accommodations.

https://15445.courses.cs.cmu.edu/fall2022/midterm-guide.html

MIDTERM EXAM

What to bring:

→ CMU ID
→ Calculator
→ One 8.5x11" page of handwritten notes (double-sided)

What not to bring:

→ Live animals
→ Your wet laundry
→ Votive Candles (aka "Jennifer Lopez" Candles)

RELATIONAL MODEL

Integrity Constraints

Relation Algebra

SQL

Basic operations:
→ SELECT / INSERT / UPDATE / DELETE
→ WHERE predicates
→ Output control

More complex operations:
→ Joins
→ Aggregates
→ Common Table Expressions

STORAGE

Buffer Management Policies
→ LRU / LRU-K / CLOCK

On-Disk File Organization

Page Layout
→ Slotted Pages
→ Log-Structured

HASHING

Static Hashing
→ Linear Probing
→ Robin Hood
→ Cuckoo Hashing

Dynamic Hashing
→ Extendible Hashing
→ Linear Hashing

TREE INDEXES

B+Tree

→ Insertions / Deletions
→ Splits / Merges
→ Difference with B-Tree
→ Latch Crabbing / Coupling

SORTING

Two-way External Merge Sort

General External Merge Sort

Cost to sort different data sets with different number of buffers.

JOINS

Nested Loop
→ Block
→ Index

Sort-Merge

Hash
→ Basic
→ Partitioned / GRACE
→ Hybrid

Execution costs under different conditions.

QUERY PROCESSING

Processing Models
→ Advantages / Disadvantages

Access Methods
→ Sequential Scan
→ Index Scan
→ Multi-Index Scan

NEXT CLASS

Parallel Query Execution