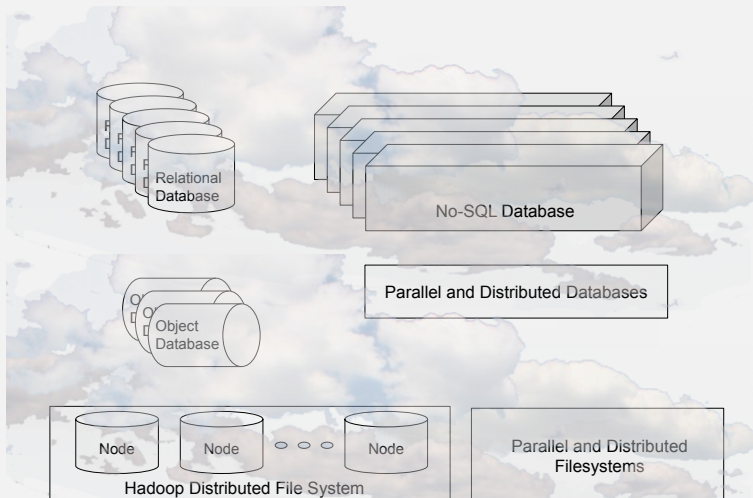


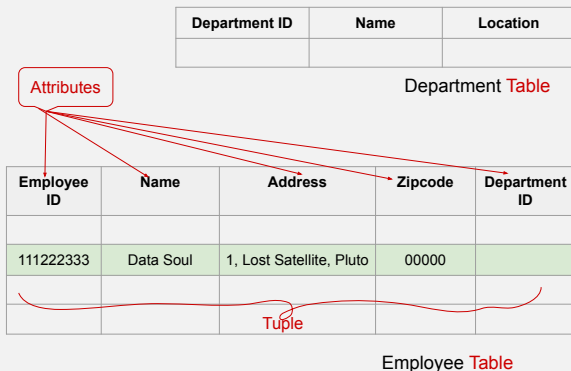
MapReduce for Data Warehouses



Data Warehouses: Hadoop and Relational Databases

- ▶ In an enterprise setting, a **data warehouse** serves as a vast repository of data, holding everything from sales transactions to product inventories.
- ▶ Data warehouses form a foundation for business intelligence applications designed to provide decision support.
- ▶ Traditionally, data warehouses have been implemented through relational databases, particularly those optimized for a specific workload known as **online analytical processing** (OLAP).
- ▶ A number of vendors offer parallel databases, but customers find that they often cannot cost-effectively scale to the crushing amounts of data an organization needs to deal with today. Hadoop (and Spark) is a scalable and low-cost alternative.
- ▶ Facebook developed Hive (an open source project), which allows the data warehouse stored in Hadoop to be accessed via SQL queries (that get transformed into MapReduce operations under the hood).
- ▶ However, in many cases Hadoop and RDBMS co-exist, feeding into one another.

Relational Database



Relational database: A set of tables, defined by a **schema**

- ▶ Relational databases are based on the concept of relational algebra on sets.
- ▶ The terms table, relation, set are often used interchangeably.
- ▶ The terms row, tuple, record are often used interchangeably.
- ▶ **SQL**: Structured Query Language – the standard for manipulating relational databases.



- ▶ Write SQL queries to create the schema for the example we just covered.
- ▶ Write a few sample SQL queries. For example:
 - ▶ Print the department table.
 - ▶ Print all the addresses found in the Employee table. Could there be any duplicates?
 - ▶ Print all (unique) zipcodes where employees live.
 - ▶ Print all the name and department IDs in the Employee table. Would they be unique?
 - ▶ Print the employee ID, name and the name of the department where they work.

Here is a good SQL tutorial. <https://www.sqltutorial.org/>

Relational MapReduce Patterns

Basic relational algebra operations that form the basis for relational databases.

- ▶ Selection
- ▶ Projection
- ▶ Union
- ▶ Intersection
- ▶ Difference
- ▶ GroupBy and Aggregation
- ▶ Join - Inner, Left (Right) Outer, Full Outer Join, Cross Join, Self Join

We will also show the corresponding SQL database queries. Then we will implement them using MapReduce.

More on Joins

- ▶ **Inner Join**: returns the intersecting rows from the two tables.
- ▶ **Left Outer**: returns all rows from the left table whether or not there is a matching row in the right table. (Similarly for a right outer join)
- ▶ **Full Outer Join**: returns all rows from the joined tables whether or not the other table has the matching row.
- ▶ **Cross Join**: returns the Cartesian product of two tables. For tables of size n and m , their result has $n \times m$ rows.
- ▶ **Self Join**: join a table to itself using either an inner join or left join clause

SQL also does an implicit join if we just use the WHERE clause on multiple tables – it defaults to a CROSS JOIN. This style of writing SQL is discouraged. Read about each join in detail in the SQL tutorial.

Selection

```
select *  
from Table_T  
where (predicate is true);
```

Assume that key for Map is row#, value is the table row (tuple).
How to do this operation in MapReduce? Do we need a Reduce?



```
class Mapper  
    method Map(rowkey key, tuple t)  
        if t satisfies the predicate  
            Emit(tuple t, null)
```

Projection

Projection takes a table (relation) and a (possibly empty) list of attributes of that table as input. It outputs a table containing only the specified list of attributes with duplicate tuples removed.

```
select  distinct A1, A2, A3  // where {A1, A2, A3} is a subset
from    Table_T;  // of the attributes for the table
```

Projection is just a little bit more complex than selection, since we need a Reducer to eliminate possible duplicates.

```
class Mapper
  method Map(rowkey key, tuple t)
    tuple g = project(t) // extract required fields to tuple g
    Emit(tuple g, null)

class Reducer
  method Reduce(tuple t, array n)  // n is an array of nulls
    Emit(tuple t, null) //skip duplicates (how?)
```


Union

```
select * from Table_T1
Union
select * from Table_T2
```

Mappers are fed by all rows of the two sets to be united. Reducer is used to eliminate duplicates.

```
class Mapper
    method Map(rowkey key, tuple t)
        Emit(tuple t, null)

class Reducer
    method Reduce(tuple t, array n) // n is an array of
        Emit(tuple t, null)         // one or two nulls
```

Intersection

```
select * from Table_T1
Intersection
select * from Table_T2
```

Mappers are fed by all rows of the two tables to be intersected. Reducer emits only rows that occurred twice. It is possible only if both sets contain this row because the row includes primary key and can occur in one set only once.

```
class Mapper
    method Map(rowkey key, tuple t)
        Emit(tuple t, null)

class Reducer
    method Reduce(tuple t, array n) // n is an array of
        if n.size() = 2              // one or two nulls
            Emit(tuple t, null)
```

Difference

```
select * from Table_T1
Except
select * from Table_T2
```

Suppose we have two tables — R and S. We want to compute difference R - S. Mapper emits all tuples with a tag, which is a name of the set this row came from. Reducer emits only rows that came from R but not from S.

```
class Mapper
  method Map(rowkey key, tuple t)
    //t.SetName is either 'R' or 'S'
    Emit(tuple t, string t.SetName)

//array n can be ['R'], ['S'], ['R','S'], or ['S','R']
class Reducer
  method Reduce(tuple t, array n)
    if n.size() = 1 and n[1] = 'R'
      Emit(tuple t, null)
```

Group By and Aggregation

```
select pub_id, type, avg(price), sum(total_sales)
from titles
group by pub_id, type
```

- ▶ Mapper extracts from each tuple the values for group by fields and aggregate fields and emits them.
- ▶ Reducer receives values to be aggregated already grouped and calculates an aggregation function.
- ▶ Typical aggregation functions like sum or max can be calculated in a streaming fashion. In some cases a two phase MapReduce job may be required (similar to Unique Items Counting).

```
class Mapper
  method Map(null, tuple[value GroupBy, value AggregateBy, value ...])
    Emit(value GroupBy, value AggregateBy)
```

```
class Reducer
  method Reduce(value GroupBy, [v1, v2,...])
    result = aggregate() //sum, max, ...
    Emit(value GroupBy, result)
```

Join

- ▶ A *Join* is a means for combining fields from two tables by using values common to each. ANSI standard SQL specifies four types of JOIN: INNER, OUTER, LEFT, and RIGHT. As a special case, a table can JOIN to itself in a self-join.
- ▶ An example:

```
CREATE TABLE department (  
    DepartmentID INT,  
    DepartmentName VARCHAR(20));
```

```
CREATE TABLE employee (  
    LastName VARCHAR(20),  
    DepartmentID INT);
```

```
SELECT *  
FROM employee  
INNER JOIN department ON  
employee.DepartmentID = department.DepartmentID;
```

```
--implicit join  
SELECT *  
FROM employee, department  
WHERE employee.DepartmentID = department.DepartmentID;
```

More on Joins

- ▶ Relational databases are often **normalized** to eliminate duplication of information when objects may have one-to-many relationships.
- ▶ Joining two tables effectively creates another table which combines information from both tables. This is at some expense in terms of the time it takes to compute the join.
- ▶ While it is also possible to simply maintain a **denormalized** table if speed is important, duplicate information may take extra space, and add the expense and complexity of maintaining data integrity if data that is duplicated later changes.
- ▶ Three fundamental algorithms for performing a join operation are: *nested loop join*, *sort-merge join* and *hash join*.

Join Example

User Demographics.

- ▶ Let R represent a collection of user profiles, in which case the key value k could be interpreted as the primary key (e.g., user id).
 - ▶ The tuples might contain demographic information such as age, gender, income, etc.
- ▶ The other data set, L , might represent logs of online activity. Each tuple might correspond to a page view of a particular URL and may contain additional information such as time spent on the page, ad revenue generated, etc.
 - ▶ The key value k in these tuples could be interpreted as the **foreign key** that associates each individual page view with a user.
- ▶ Joining these two data sets would allow an analyst, for example, to break down online activity in terms of demographics.

Join Examples



Movie Data Mining. Suppose we have three tables shown below and we want to find the top ten movies (by average rating):

Ratings [UserID, MovieID, Rating, Timestamp]

Users [UserID, Gender, Age, Occupation, Zip-code]

Movies [MovieID, Title, Genres]

Team up with another student and figure out the SQL query to get the answer.

Hint: <https://www.sqltutorial.org/sql-aggregate-functions/sql-avg/>

Repartition Join

Join of two sets R and L on some key k.

- ▶ Mapper goes through all tuples from R and L, extracts key k from the tuples, marks tuple with a tag that indicates a set this tuple came from ('R' or 'L'), and emits tagged tuple using k as a key.
- ▶ Reducer receives all tuples for a particular key k and puts them into two buckets – for R and for L. When the two buckets are filled, Reducer runs nested loop over them and emits a cross join of the buckets.
- ▶ Each emitted tuple is a concatenation R-tuple, L-tuple, and key k.

```
class Mapper
```

```
  method Map(null, tuple [join_key k, value v1, value v2,...])  
    Emit(join_key k, tagged_tuple [set_name tag, values [v1, v2, ...] ] )
```

```
class Reducer
```

```
  method Reduce(join_key k, tagged_tuples [t1, t2,...])
```

```
    H = new AssociativeArray : set_name -> values
```

```
    //separate values into 2 arrays
```

```
    for all tagged_tuple t in [t1, t2,...]
```

```
      H{t.tag}.add(t.values)
```

```
    //produce a cross-join of the two arrays
```

```
    for all values r in H{'R'}
```

```
      for all values l in H{'L'}
```

```
        Emit(null, [k, r, l] )
```

Replicated Join

- ▶ Let's assume that one of the two sets, say R, is relatively small. This is fairly typical in practice.
- ▶ If so, R can be distributed to all Mappers and each Mapper can load it and index by the join key (e.g. in a hash table). After this, Mapper goes through tuples of the set L and joins them with the corresponding tuples from R that are stored in the hash table.
- ▶ This approach is very effective because there is no need for sorting or transmission of the set L over the network. Also known as **memory-backed join** or **simple hash join**.

```
class Mapper
  method Initialize
    H = new AssociativeArray : join_key -> tuple from R
    R = loadR() //load table in memory
    for all [ join_key k, tuple [r1, r2,...] ] in R
      H{k} = H{k}.append( [r1, r2,...] )

  method Map(join_key k, tuple l)
    for all tuple r in H{k}
      Emit(null, tuple [k, r, l] )
```

Join Without Scalability Issues

Suppose we have two relations, generically named S and T .

(k_1, s_1, \mathbf{S}_1)

(k_2, s_2, \mathbf{S}_2)

(k_3, s_3, \mathbf{S}_3)

...

where k is the key we would like to join on, s_n is a unique id for the tuple, and the \mathbf{S}_n after s_n denotes other attributes in the tuple (unimportant for the purposes of the join).

(k_1, t_1, \mathbf{T}_1)

(k_3, t_2, \mathbf{T}_2)

(k_8, t_3, \mathbf{T}_3)

...

where k is the join key, t_n is a unique id for the tuple, and the \mathbf{T}_n after t_n denotes other attributes in the tuple.

Reduce-Side Join

- ▶ We map over both data sets and emit the join key as the intermediate key, and the tuple itself as the intermediate value. Since MapReduce guarantees that all values with the same key are brought together, all tuples will be grouped by the join key—which is exactly what we need to perform the join operation.
- ▶ This approach is known as a **parallel sort-merge join** in the database community.
- ▶ There are three cases to consider:
 - ▶ **One to one**
 - ▶ **One to many**
 - ▶ **Many to many**

Reduce-side Join: one to one

- ▶ The reducer will be presented keys and lists of values along the lines of the following:

$k_{23} \rightarrow [(s_{64}, \mathbf{S}_{64}), (t_{84}, \mathbf{T}_{84})]$

$k_{37} \rightarrow [(s_{68}, \mathbf{S}_{68})]$

$k_{59} \rightarrow [(t_{97}, \mathbf{T}_{97}), (s_{81}, \mathbf{S}_{81})]$

$k_{61} \rightarrow [(t_{99}, \mathbf{T}_{99})]$

...

- ▶ If there are two values associated with a key, then we know that one must be from S and the other must be from T . We can proceed to join the two tuples and perform additional computations (e.g., filter by some other attribute, compute aggregates, etc.).
- ▶ If there is only one value associated with a key, this means that no tuple in the other data set shares the join key, so the reducer does nothing.

Reduce-side Join: one to many

- ▶ In the mapper, we instead create a composite key consisting of the join key and the tuple id (from either S or T). Two additional changes are required:
 - ▶ First, we must define the sort order of the keys to first sort by the join key, and then sort all tuple ids from S before all tuple ids from T .
 - ▶ Second, we must define the partitioner to pay attention to only the join key, so that all composite keys with the same join key arrive at the same reducer.
- ▶ After applying the value-to-key conversion design pattern, the reducer will be presented with keys and values along the lines of the following:
 - $(k_{82}, s_{105}) \rightarrow [(S_{105})]$
 - $(k_{82}, t_{98}) \rightarrow [(T_{98})]$
 - $(k_{82}, t_{101}) \rightarrow [(T_{101})]$
 - $(k_{82}, t_{137}) \rightarrow [(T_{137})]$
 - ...
- ▶ Whenever the reducer encounters a new join key, it is guaranteed that the associated value will be the relevant tuple from S . The reducer can hold this tuple in memory and then proceed to cross it with tuples from T in subsequent steps (until a new join key is encountered).
- ▶ Since the MapReduce execution framework performs the sorting, there is no need to buffer tuples (other than the single one from S). Thus, we have eliminated the scalability bottleneck.

Reduce-side Join: many to many

- ▶ All the tuples from S with the same join key will be encountered first, which the reducer can buffer in memory.
- ▶ As the reducer processes each tuple from T , it is crossed with all the tuples from S .
- ▶ Of course, we are assuming that the tuples from S (with the same join key) will fit into memory, which is a limitation of this algorithm (and why we want to control the sort order so that the smaller data set comes first).

Hive

- ▶ Hive was created at Facebook to make it possible for analysts with strong SQL skills (but meager Java programming skills) to run queries on the huge volumes of data that Facebook stored in HDFS.
- ▶ Hive is a successful open source Apache project used by many organizations as a general-purpose, scalable data processing platform.
- ▶ Hive Query Language is very similar to SQL. The data scientist can write Hive queries in the hive shell (or Hive web interface or via an API to a Hive server). The queries get converted into MapReduce operations and run on Hadoop HDFS file system.

Hadoop and Hive: A Local Case Study

- ▶ Simulated a business intelligence problem that was given to us by a local software company. Currently they solve the problem using a traditional database. If we were to store the data in HDFS, we could exploit the parallel processing capability of MapReduce/Hive.
- ▶ **Setup.** A \$5000 database server with 8 cores and 8G of memory versus four commodity dual-core nodes with 2G of memory and worth about \$1200 each for the HDFS cluster.
- ▶ **Results.** Increase data size until Hadoop/Hive outperforms the database solution.

Data size	Hadoop Speedup	Hive Speedup
3G	0.6	0.1
4G	2.6	0.4
10G	17.5	2.5
20G	23.9	3.8

- ▶ The Hive-based solution required no programming! The MapReduce solution did require programming but was simpler than traditional parallel programming.

- ▶ **HBase** is a distributed column-oriented database built on top of HDFS. HBase is the Hadoop application to use when you require real-time read/write random access to very large data sets.
- ▶ HBase is not relational and does not support SQL but it can support very large, sparsely populated tables on clusters made from commodity hardware.
- ▶ Integrated with Hadoop MapReduce for powerful access.

RDBMS Story

- ▶ **Initial public launch.**
Move from local workstation to shared, remotely hosted MySQL instance with a well-defined schema.
- ▶ **Service becomes more popular; too many reads hitting the database.**
Add *memcached* to cache common queries. Reads are now no longer strictly ACID (Atomicity, Consistency, Isolation, Durability); cached data must expire.
- ▶ **Service continues to grow in popularity; too many writes hitting the database.**
Scale MySQL vertically by buying a beefed-up server with 64 cores, 256 GB of RAM, and banks of fast hard drives. Costly.
- ▶ **New features increases query complexity; now we have too many joins.**
Denormalize your data to reduce joins. (That's not what they taught me in DBA school!)
- ▶ **Rising popularity swamps the server; things are too slow.**
Stop doing any server-side computations.
- ▶ **Some queries are still too slow.**
Periodically prematerialize the most complex queries, and try to stop joining in most cases.
- ▶ **Reads are OK, but writes are getting slower and slower.**
Drop secondary indexes and triggers (no indexes?)

At this point, there are no clear solutions for how to solve your scaling problems. In any case, you'll need to begin to scale horizontally. You can attempt to build some type of partitioning on your largest tables, or look into expensive solutions that provide multiple master capabilities.

HBase Story

- ▶ **No real indexes.**

Rows are stored sequentially, as are the columns within each row. Therefore, no issues with index bloat, and insert performance is independent of table size.

- ▶ **Automatic partitioning.**

As your tables grow, they will automatically be split into regions and distributed across all available nodes.

- ▶ **Scale linearly and automatically with new nodes.**

Add a node, point it to the existing cluster, and run the regionserver. Regions will automatically rebalance, and load will spread evenly.

- ▶ **Commodity hardware.**

Clusters are built on \$1,000–\$5,000 nodes rather than \$50,000 nodes. RDBMSs are I/O hungry, requiring more costly hardware. Easy for elastic scaling in the cloud.

- ▶ **Fault tolerant.**

Lots of nodes means each is relatively insignificant. No need to worry about individual node downtime.

- ▶ **Batch processing.**

MapReduce (and Spark) integration allows fully parallel, distributed jobs against your data with locality awareness.

If you stay up at night worrying about your database (uptime, scale, or speed), you would seriously consider making a jump from the RDBMS world to HBase (or another no-SQL distributed database)

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