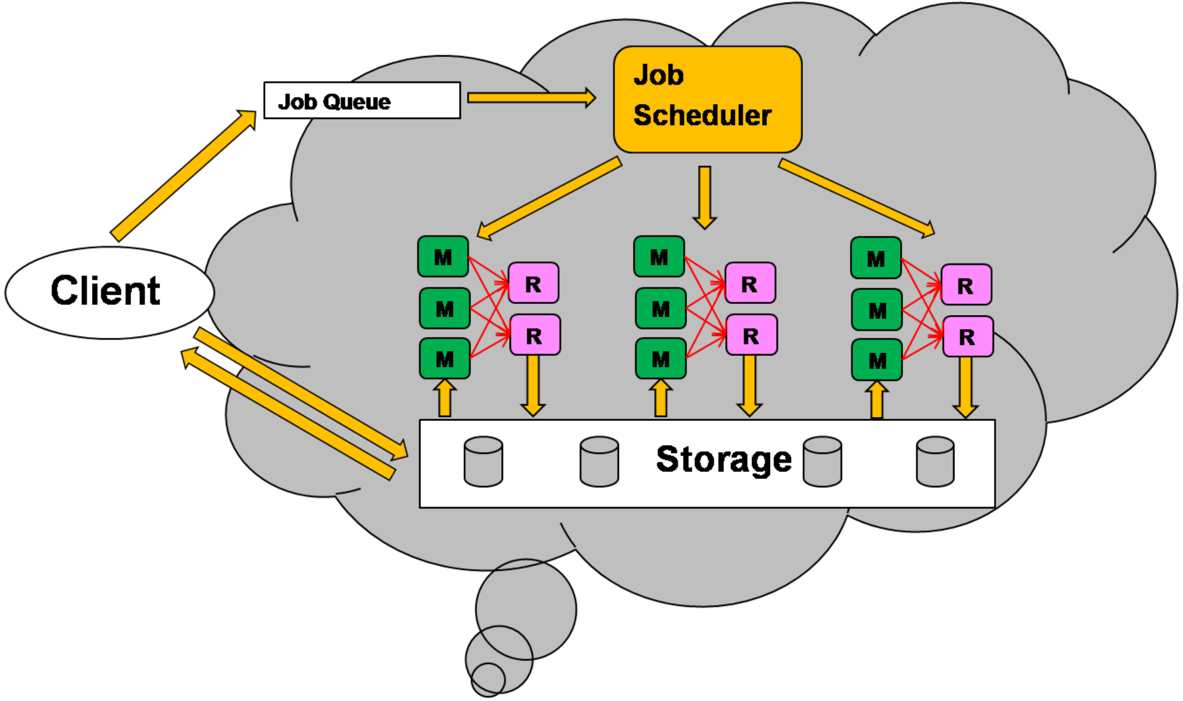
Relational Data Processing on MapReduce



http://www.csd.uoc.gr/~hy562

University of Crete, Fall 2024

Peta-scale Data Analysis

12+ TBs
of tweet data every day

100 PBs
of data every day

***30 billion* RFID tags in 2014 (1.3B in 2005)**

***4.6 billion* camera phones world wide**

***100s of millions of GPS enabled* devices sold annually**

***25+ TBs* of log data every day generated by a new user being added every sec. for 3 years**

***200 million* smart meters in 2014**

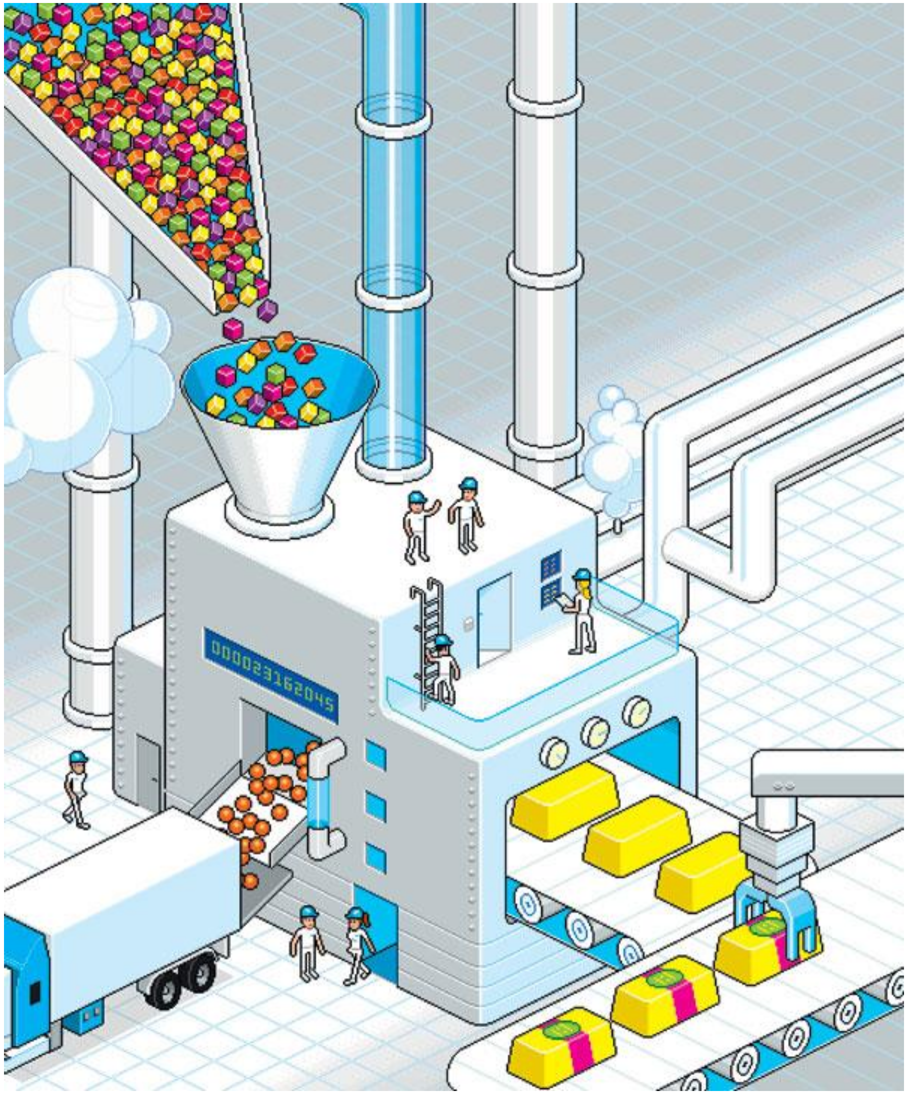
***2+ billion* people on the Web in 2011**

4 billion views/day
YouTube is the 2nd most used search engine next to Google

Big Data Analysis

- A lot of these datasets have some structure
  - Query logs
  - Point-of-sale records
  - User data (e.g., demographics)
  - …

- How do we perform data analysis at scale?
  - Relational databases and SQL
  - MapReduce (Hadoop) & Spark



Relational Databases vs. MapReduce

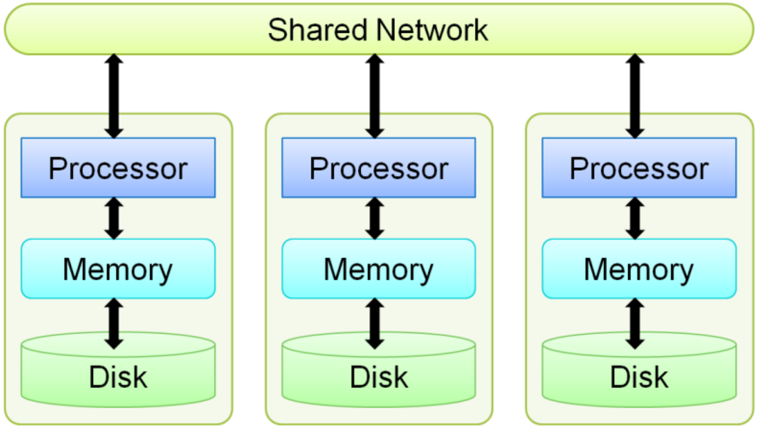
- Relational databases:
  - Multi-purpose: analysis and transactions; batch and interactive
  - Data integrity via ACID transactions
  - Lots of tools in software ecosystem (for ingesting, reporting, etc.)
  - Supports SQL (and SQL integration, e.g., JDBC)
  - Automatic SQL query optimization

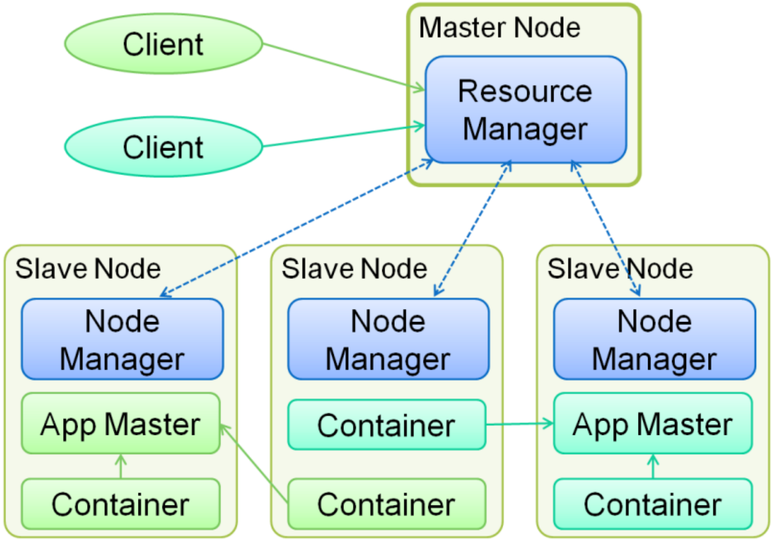
- MapReduce & Spark:
  - Designed for large clusters, fault tolerant
  - Data is accessed in “native format”
  - Supports many query languages
  - Programmers retain control over performance

Parallel Relational Databases vs. MapReduce

- Parallel relational databases
  - ◆Schema on “write”
  - ◆Failures are relatively infrequent
  - ◆“Possessive” of data
  - ◆Mostly proprietary
- MapReduce
  - ◆Schema on “read”
  - ◆Failures are relatively common
  - ◆In situ data processing
  - ◆Open source

Shared-nothing architecture for parallel processing





Hadoop v2.0 (YARN) architecture

MapReduce vs Parallel DBMS

	Parallel DBMS	MapReduce
Schema Support	✓	Not out of the box
Indexing	✓	Not out of the box
Programming Model	Declarative (SQL)	Imperative (C/C++, Java, …) Extensions through Pig and Hive
Optimizations (Compression, Query Optimization)	✓	Not out of the box
Flexibility	Not out of the box	✓
Fault Tolerance	Coarse grained techniques	✓

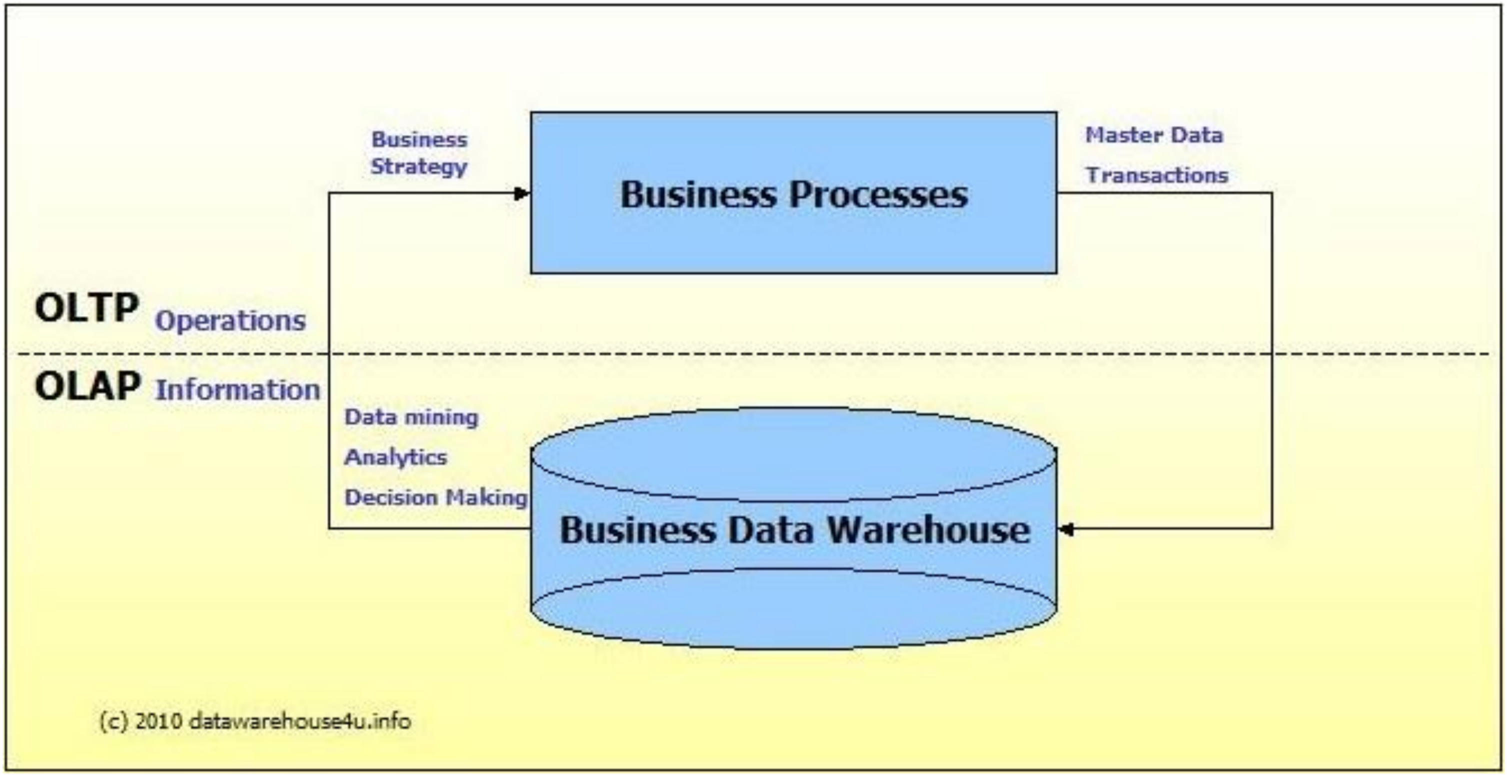
[Pavlo et al., SIGMOD 2009, Stonebraker et al., CACM 2010, …]

Database Workloads

- OLTP (online transaction processing)
  - captures, stores, and processes data from transactions in real time
  - Typical applications: e-commerce, banking, airline reservations
  - User facing: *real-time*, *low latency*, *highly concurrent*
  - Data access pattern: *random reads*, *updates*, *writes* (involving relatively small amounts of data)

- OLAP (online analytical processing)
  - uses complex queries to analyze aggregated historical data
  - Typical applications: business intelligence (BI), data mining
  - Back-end processing: *batch workloads*, *less concurrency*
  - Data access pattern: *table scans*, large amounts of data involved per query

One Database or Two?



(c) 2010 datawarehouse4u.info

- Downsides of co-existing OLTP and OLAP workloads
  - *Poor memory management*
  - *Conflicting data access patterns*
  - *Variable latency*
- Solution: separate databases
  - *User-facing OLTP database* for high-volume transactions
  - *Data warehouse for OLAP workloads*
  - How do we *connect the two?*

OLTP/OLAP Integration


OLTP

ETL

(Extract, Transform, Load)

OLAP

- OLTP database for user-facing transactions
  - Retain records of all activity
  - Periodic ETL (e.g., nightly)
- Extract-Transform-Load (ETL)
  - Extract records from source
  - Transform: clean data, check integrity, aggregate, etc.
  - Load into OLAP database
- OLAP database for data warehousing
  - Business intelligence: reporting, ad hoc queries, data mining, etc.
  - Feedback to improve OLTP services

OLTP/OLAP Architecture: Hadoop?

What about here?

OLTP

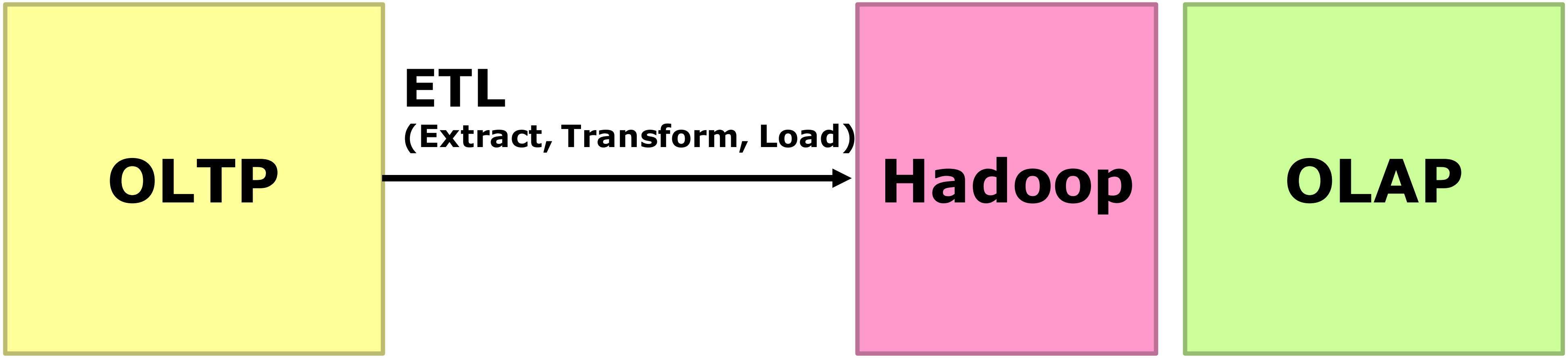
ETL

(Extract, Transform, Load)

OLAP

Hadoop here?

OLTP/OLAP/Hadoop Architecture



OLTP

ETL

(Extract, Transform, Load)

Hadoop

OLAP

- Why does this make sense?

ETL Bottleneck

- ETL is often a nightly task:
    - processing 24h of data may take longer than 24h!
- Often, with noisy datasets, ETL is the analysis!
    - ETL necessarily involves brute-force data scans: L, then E and T?
- Using Hadoop:
    - Most likely, you already have some data warehousing solution
    - *Ingest is limited by speed of HDFS*
    - *Scales out* with more nodes
    - *Massively parallel* and much cheaper than parallel databases
    - Ability to use *any processing tool*
    - ETL is a *batch process* anyway!

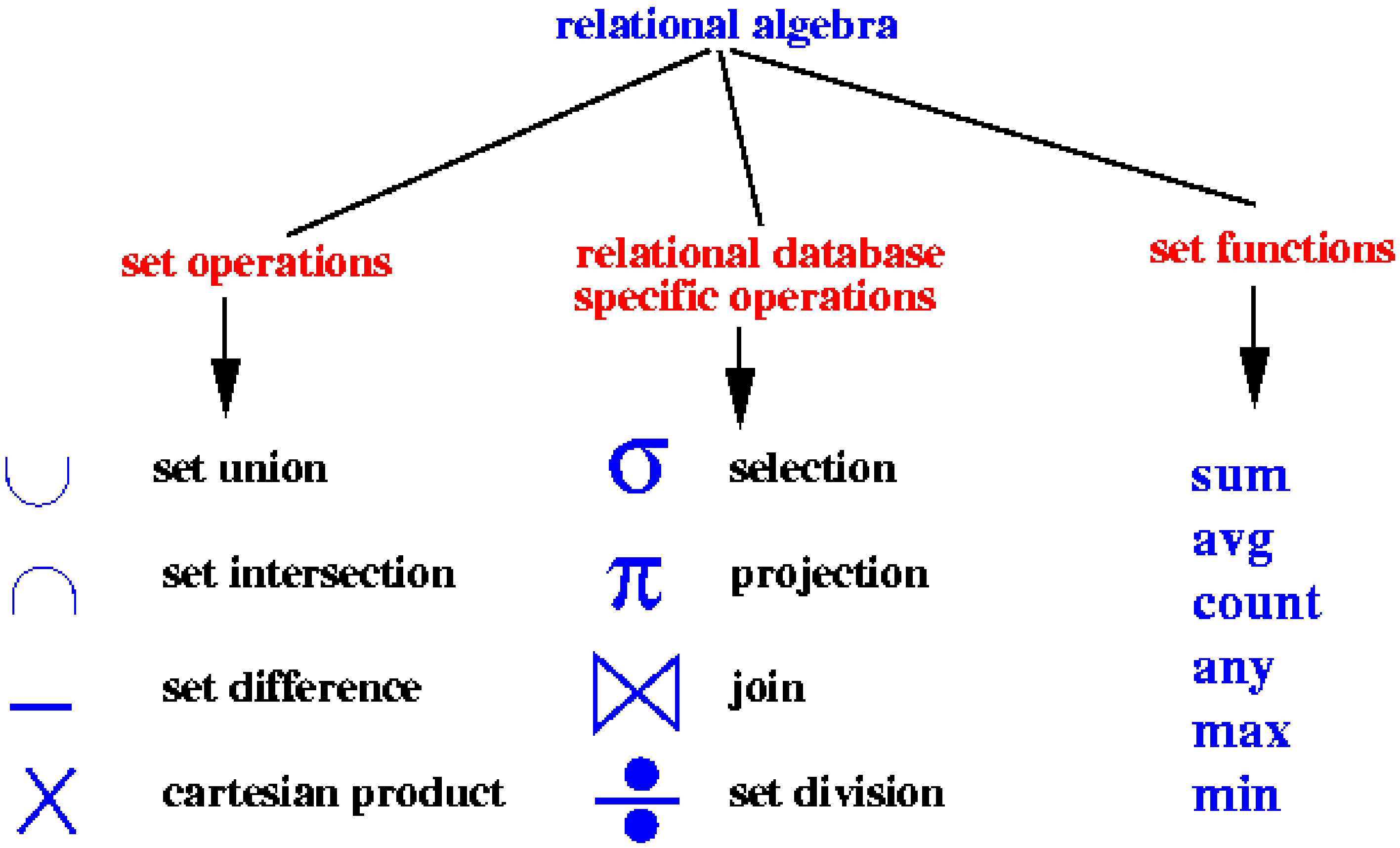
MapReduce Algorithms for Processing Relational Data

Working Scenario

- Two tables:
  - User demographics (gender, age, income, etc.)
  - User page visits (URL, time spent, etc.)

- Analyses we might want to perform:
  - Statistics on demographic characteristics
  - Statistics on page visits
  - Statistics on page visits by URL
  - Statistics on page visits by demographic characteristic
  - …

Relational Algebra

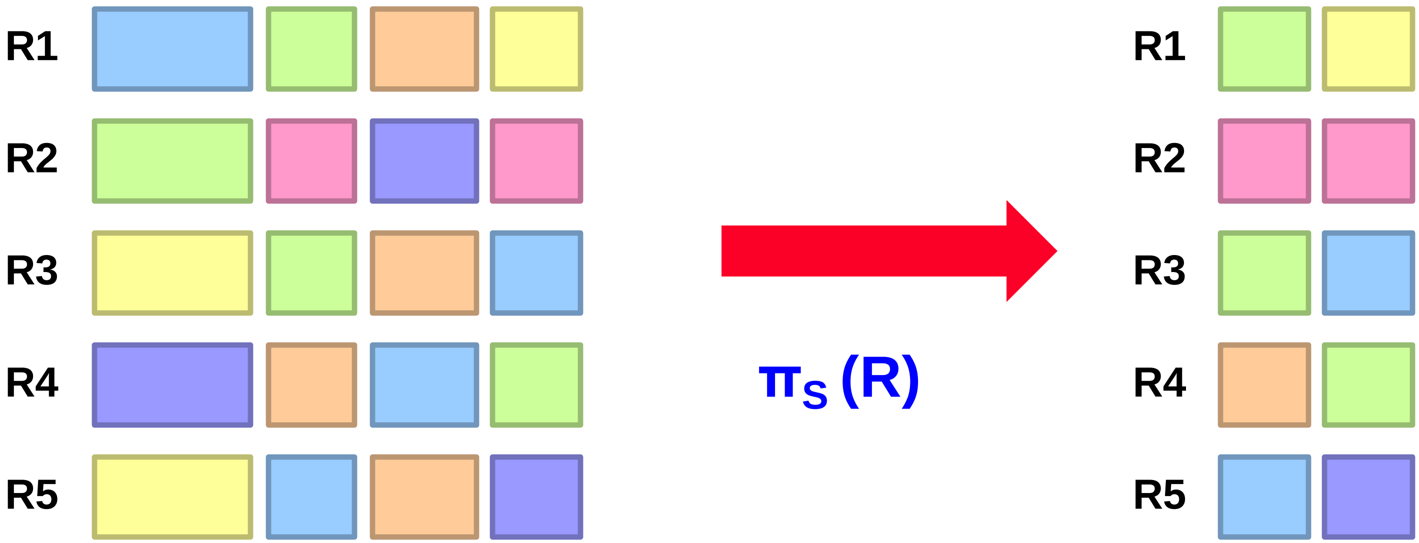


relational algebra

- set operations
  - $\cup$ set union
  - $\cap$ set intersection
  - $-$ set difference
  - $\times$ cartesian product
- relational database specific operations
  - σ selection
  - π projection
  - $\bowtie$ join
  - $\div$ set division
- set functions
  - sum
  - avg
  - count
  - any
  - max
  - min

www.mathcs.emory.edu/~cheung/Courses/377/Syllabus/4-RelAlg/intro.html

Projection



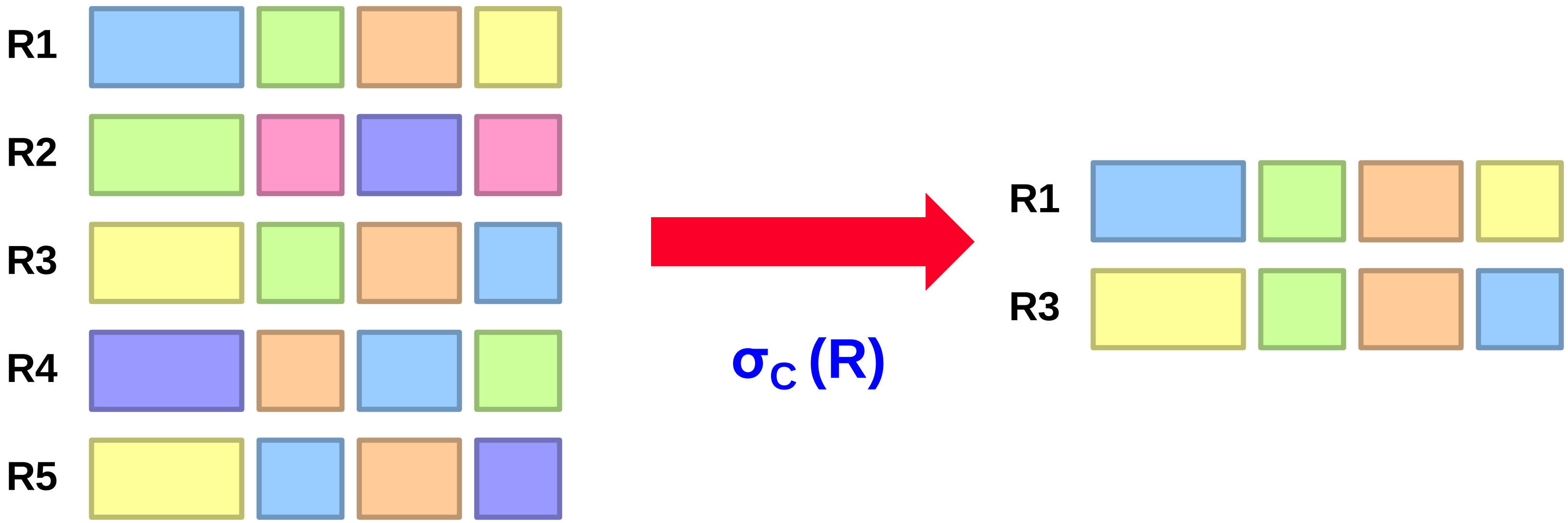
$\pi_S(R)$

Projection in MapReduce

- Easy!
  - Map over tuples, emit new tuples with the projected attributes
    - For each tuple t in R, construct a tuple t’ by eliminating those components whose attributes are not in S, emit a key/value pair (t’, t’)
  - No reducers (reducers are the *identity* function), unless for regrouping or resorting tuples
    - the Reduce operation performs duplicate elimination
  - Alternatively: perform in reducer, after some other processing

- Basically limited by HDFS streaming speeds
  - Speed of *encoding/decoding* tuples becomes important
  - Relational databases take advantage of *compression*
  - Semi-structured data? No problem!

Selection



Selection in MapReduce

- Easy!
  - Map over tuples, emit only tuples that meet selection criteria
    - For each tuple t in R, check if t satisfies C and if so, emit a key/value pair (t, t)
      - *equivalent in Spark: filter()*
  - No reducers (reducers are the *identity* function), unless for regrouping or resorting tuples
  - Alternatively: perform in reducer, after some other processing

- Basically limited by HDFS streaming speeds:
  - Speed of *encoding/decoding tuples* becomes important
  - Relational databases take advantage of *compression*
  - Semi-structured data? No problem!

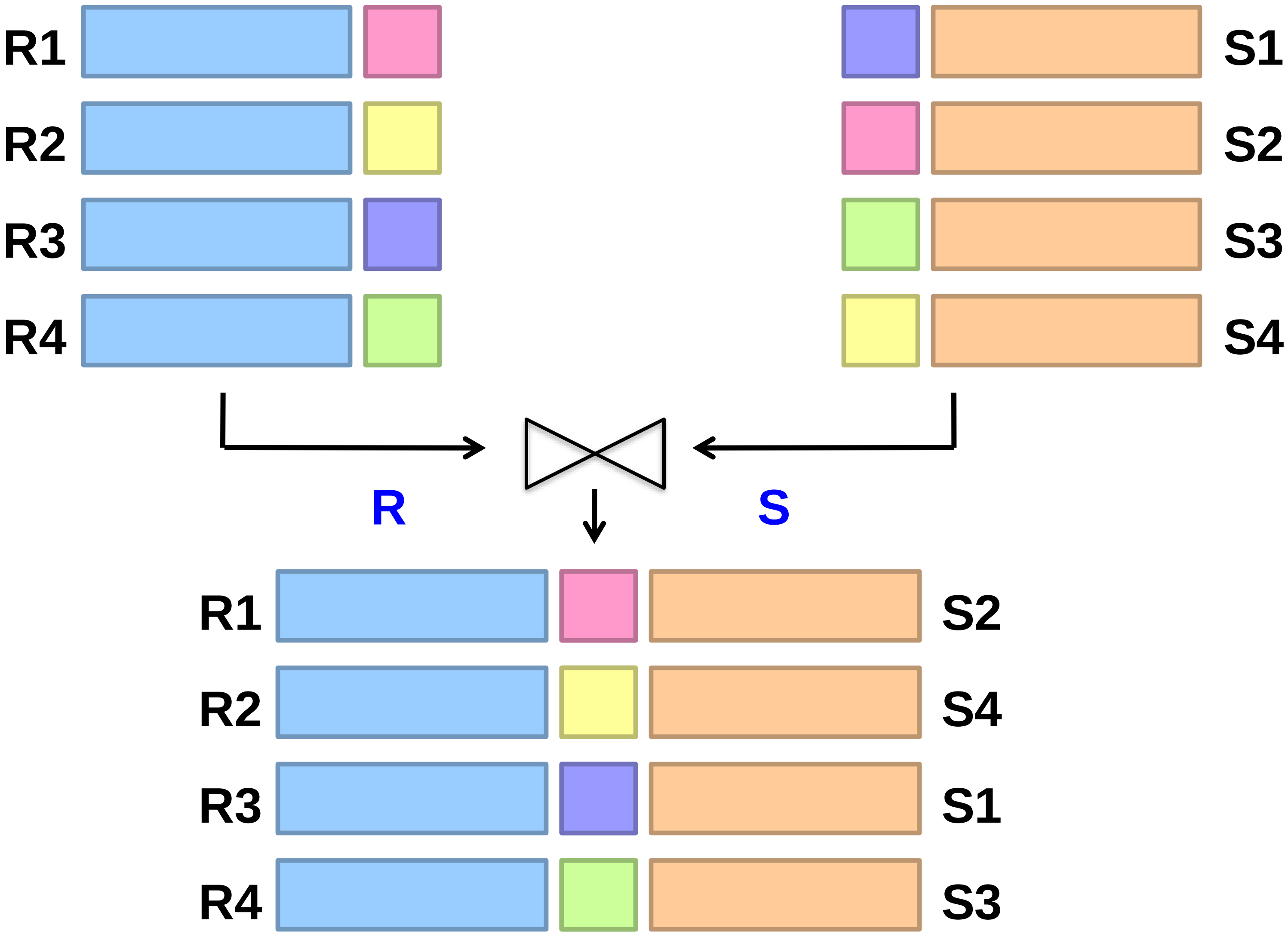
Set Operations in Map Reduce

- `R(X,Y) ∪ S(X,Y)`
  - Map: for each tuple t either in R or in S, emit (t,t)
  - Reduce: either receive (t,[t,t]) or (t,[t])
    - Always emit (t,t)
    - We perform duplicate elimination
- `R(X,Y) ∩ S(X,Y)`
  - Map: for each tuple t either in R or in S, emit (t,t)
  - Reduce: either receive (t,[t,t]) or (t,[t])
    - Emit (t,t) in the former case and nothing in the latter
- `R(X,Y) \ S(X,Y)`
  - Map: for each tuple t either in R or in S, emit (t, R or S)
  - Reduce: receive (t,[R]) or (t,[S]) or (t,[R,S])
    - Emit (t,t) only when received (t,[R]), otherwise emit nothing

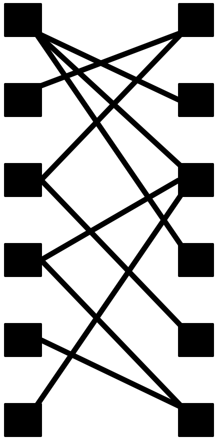
Group by… Aggregation

- Example: What is the average time spent per URL?
- In SQL:
  - `SELECT url, AVG(time) FROM visits GROUP BY url`
- In MapReduce: Let R(A, B, C) be a relation to which we apply $\gamma_{A,\theta(B)}(R)$
  - The map operation prepares the grouping e.g., emit (url, time) pairs
  - The grouping is done by the framework
  - The reducer computes the aggregation (e.g. average)
  - Eventually, optimize with combiners
  - Simplifying assumptions: *one grouping attribute* and *one aggregation* function

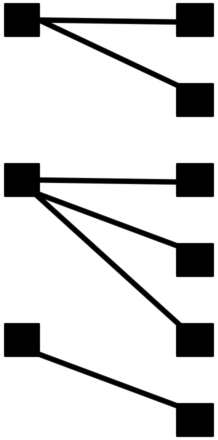
Relational Joins



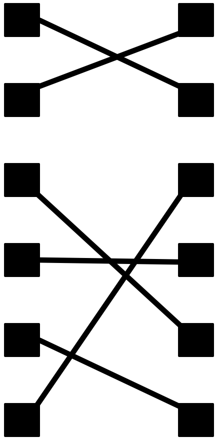
Types of Relationships



Many-to-Many



One-to-Many



One-to-One

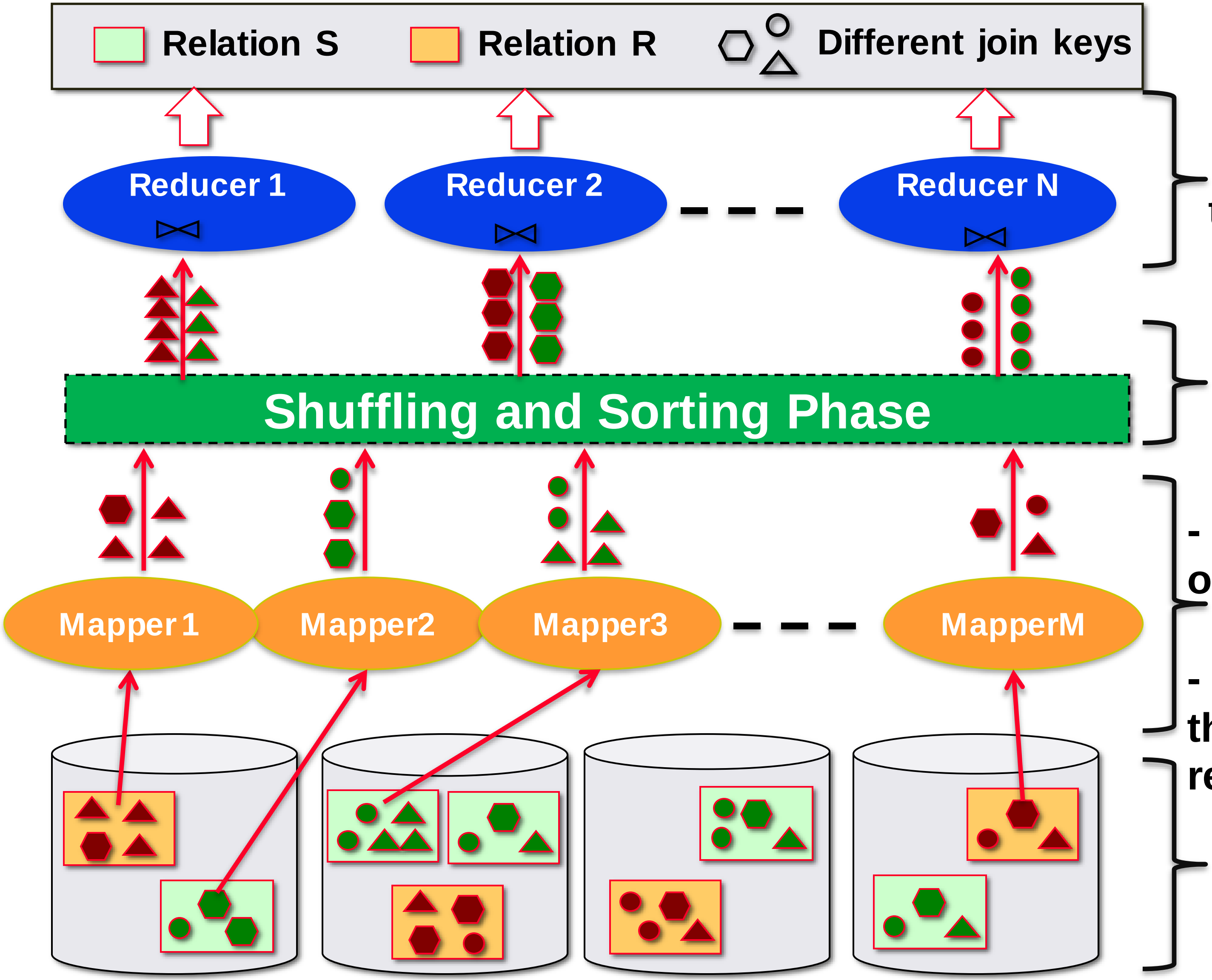
Join Algorithms in MapReduce

- “Join” usually just means equi-join, but we also want to support *other* join predicates

- Hadoop has some built-in join support, but our goal is to understand important algorithm design principles

- Algorithms
  - Reduce-side join
  - Map-side join
  - In-memory join
    - Striped variant
    - Memcached variant

Reduce-side Join



🟩 Relation S   🟧 Relation R   ⬡ ○ △ Different join keys

Reducer 1 ⋈   Reducer 2 ⋈   - - -   Reducer N ⋈

Shuffling and Sorting Phase

Mapper1   Mapper2   Mapper3   - - -   MapperM

Reducers perform the actual join

Shuffling and sorting over the network

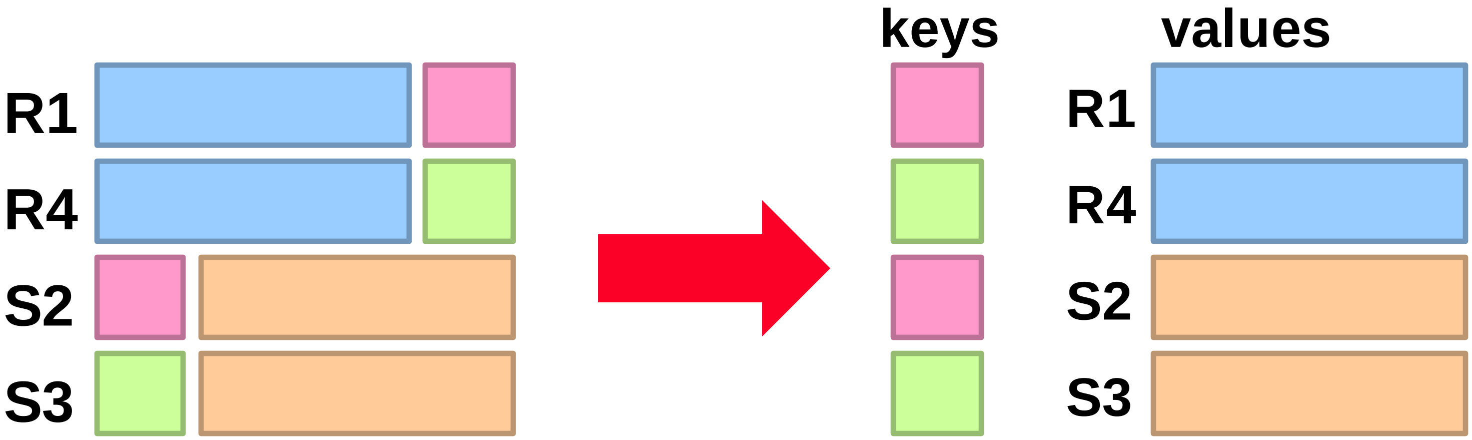
- Each mapper processes one block (split)

- Each mapper produces the join key and the record pairs

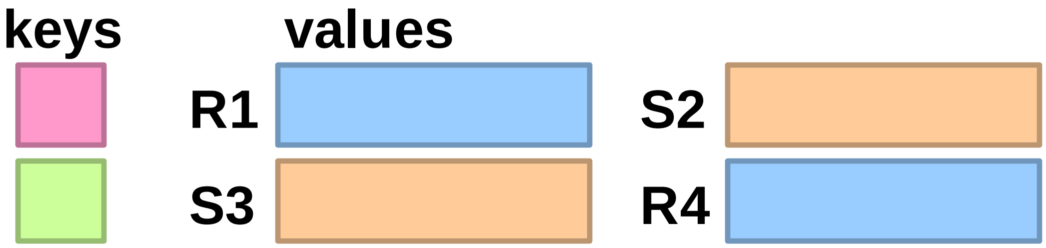
HDFS stores data blocks (Replicas are not shown)

Reduce-side Join: 1-to-1

Map



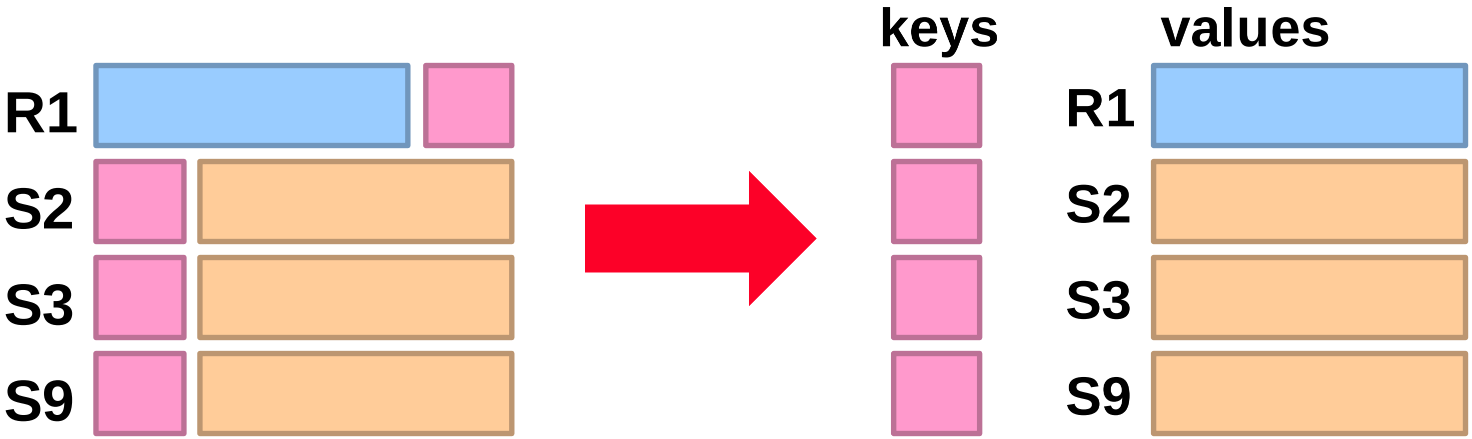
Reduce



Note: no guarantee if R is going to come first or S!

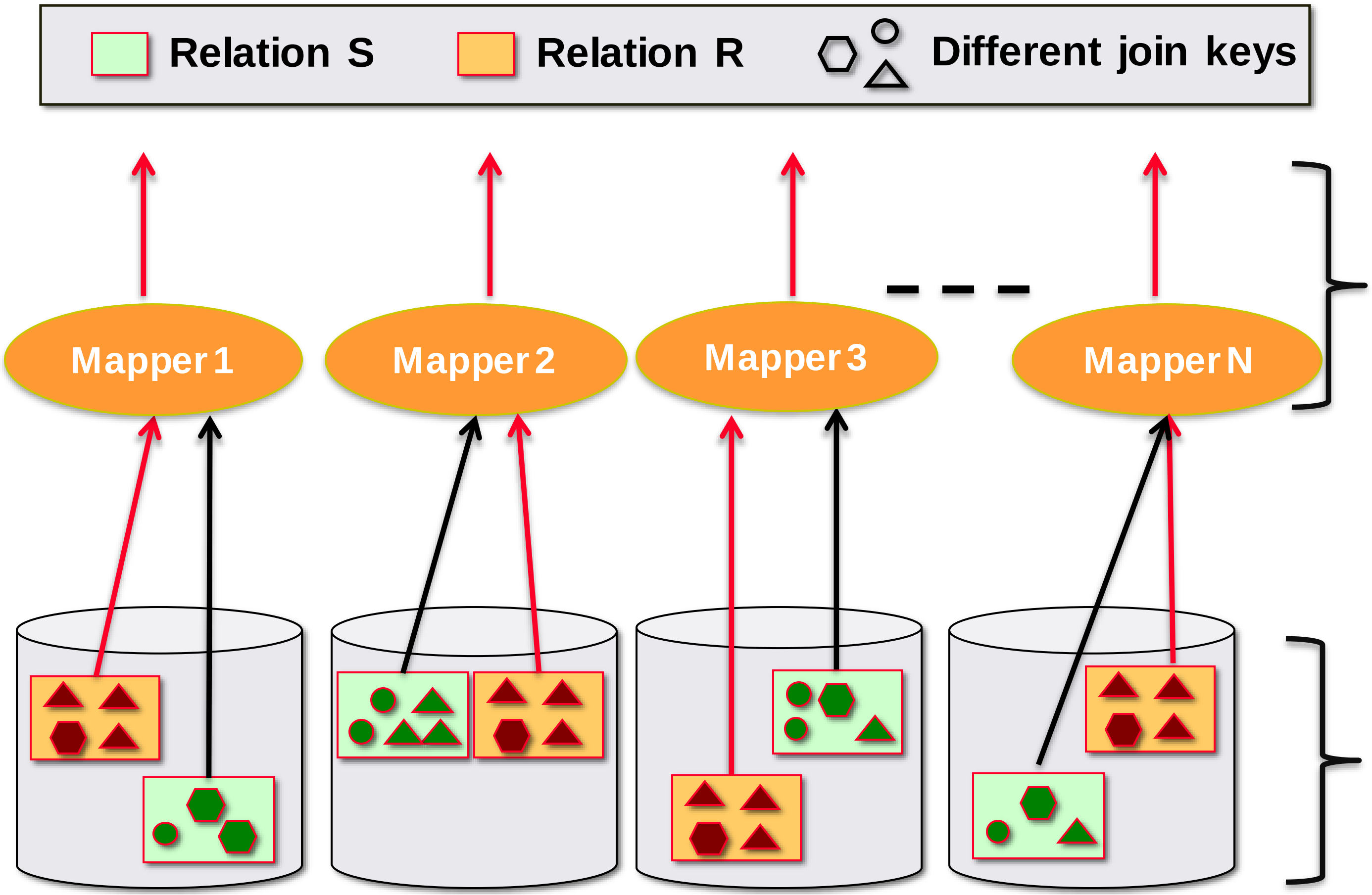
Reduce-side Join: 1-to-Many

Map



Reduce

Map-side (in-memory) Join



Load one dataset into memory, stream over other dataset

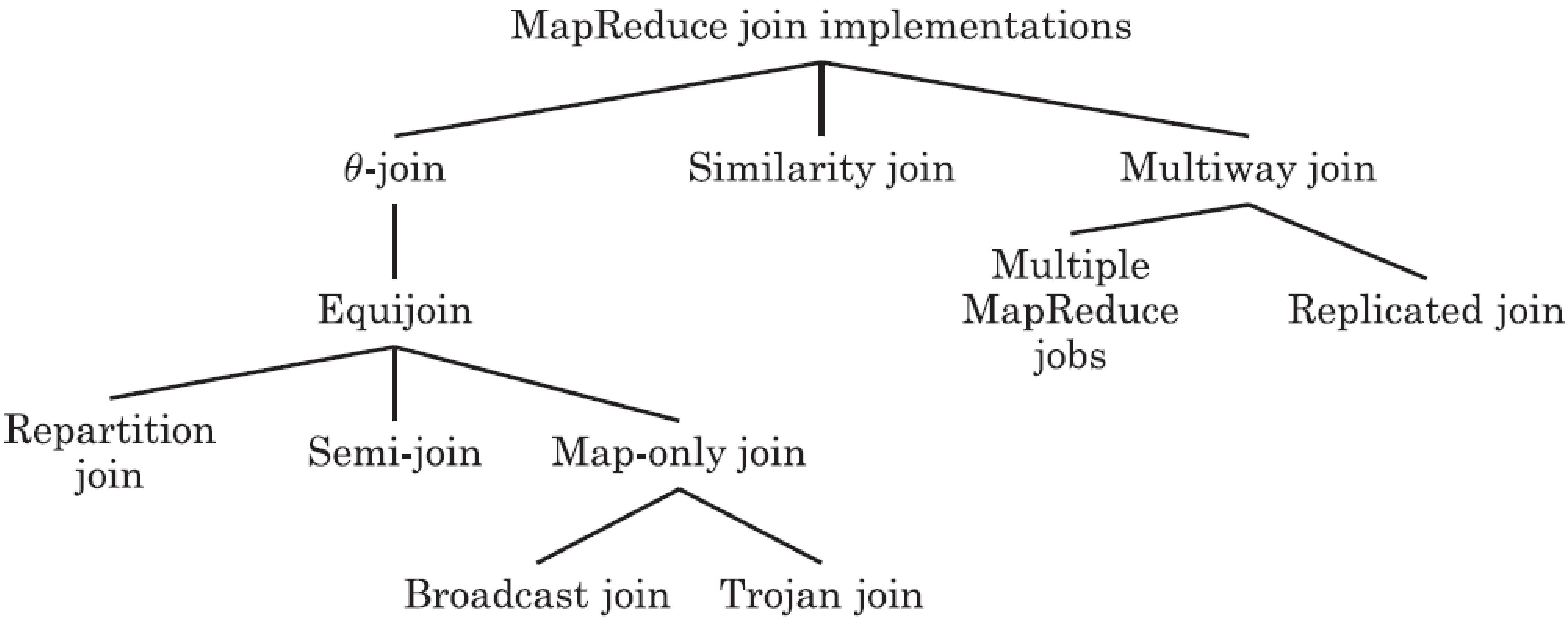
Distribute the smaller relation to all nodes

Map-side (in-memory) Join

- MapReduce implementation
  - Distribute R to all nodes (assumption: R is small!)
  - Map over S, each mapper loads R in memory, hashed by join key
  - For every tuple in S, look up join key in R
  - No reducers, unless for regrouping or resorting tuples

- Downside: need to copy R to all mappers
  - Not so bad, since R is small

Join Implementations on MapReduce



Feng Li, Beng Chin Ooi, M. Tamer Özsu, and Sai Wu. 2014. Distributed data management using MapReduce. ACM Comput. Surv. 46, 3, January 2014

Processing Relational Data: Summary

- MapReduce algorithms for processing relational data:
  - Group by, sorting, partitioning are handled automatically by shuffle/sort in MapReduce
  - Selection, projection, and other computations (e.g., aggregation), are performed either in mapper or reducer

- Complex operations require multiple MapReduce jobs
  - Example: top ten URLs in terms of average time spent
  - Opportunities for automatic optimization

- Multiple strategies for relational joins

Evolving Roles for Relational Database and MapReduce

Need for High-Level Languages

- Hadoop is great for large-data processing!
  - But writing Java programs for everything is verbose and slow
  - Analysts don't want to (or can't) write Java

- Solution: develop higher-level data processing languages
  - Hive: HQL is like SQL
  - Pig: Pig Latin is a bit like Perl
  - Spark SQL: execute SQL on top of Spark

Hive and Pig

- Hive: data warehousing application in Hadoop
  - Query language is HiveQL (aka HQL), variant of SQL
  - Tables stored on HDFS as flat files
  - Developed by Facebook, now open source

- Pig: large-scale data processing system
  - Scripts are written in Pig Latin, a dataflow language
  - Developed by Yahoo!, now open source
    - Roughly 1/3 of all Yahoo! internal jobs

- Common idea:
  - Provide higher-level language to facilitate large-data processing
  - Higher-level language “compiles down” to Hadoop jobs

Hive: Example

- Hive looks similar to an relational database
- Relational join on two tables:
  - Table of word counts from Shakespeare collection
  - Table of word counts from the bible

```
SELECT s.word, s.freq, k.freq FROM shakespeare s
  JOIN bible k ON (s.word = k.word) WHERE s.freq >= 1 AND k.freq >= 1
  ORDER BY s.freq DESC LIMIT 10;
```

```
the     25848   62394
I       23031   8854
and     19671   38985
to      18038   13526
of      16700   34654
a       14170   8057
you     12702   2720
my      11297   4135
in      10797   12445
is      8882    6884
```

Source: Material drawn from Cloudera training VM

Hive: Behind the Scenes

```
SELECT s.word, s.freq, k.freq FROM shakespeare s
  JOIN bible k ON (s.word = k.word) WHERE s.freq >= 1 AND k.freq >= 1
  ORDER BY s.freq DESC LIMIT 10;
```

(Abstract Syntax Tree)

```
(TOK_QUERY (TOK_FROM (TOK_JOIN (TOK_TABREF shakespeare s) (TOK_TABREF bible k) (= (.
(TOK_TABLE_OR_COL s) word) (. (TOK_TABLE_OR_COL k) word)))) (TOK_INSERT
(TOK_DESTINATION (TOK_DIR TOK_TMP_FILE)) (TOK_SELECT (TOK_SELEXPR (.
(TOK_TABLE_OR_COL s) word)) (TOK_SELEXPR (. (TOK_TABLE_OR_COL s) freq)) (TOK_SELEXPR
(. (TOK_TABLE_OR_COL k) freq))) (TOK_WHERE (AND (>= (. (TOK_TABLE_OR_COL s) freq) 1)
(>= (. (TOK_TABLE_OR_COL k) freq) 1))) (TOK_ORDERBY (TOK_TABSORTCOLNAMEDESC (.
(TOK_TABLE_OR_COL s) freq))) (TOK_LIMIT 10)))
```

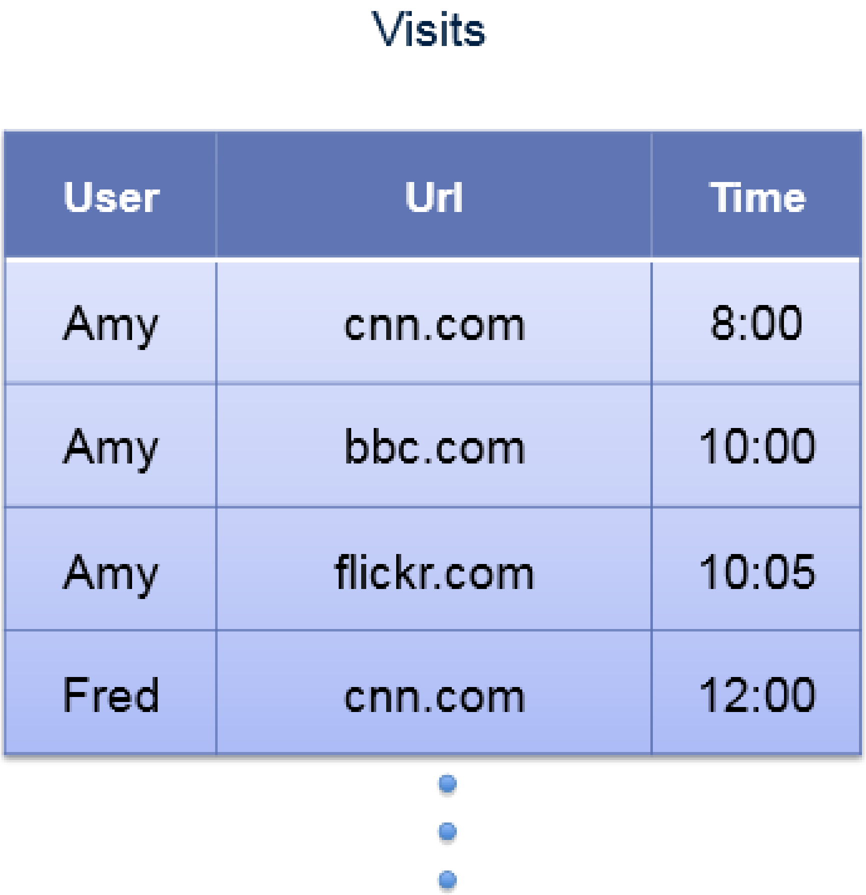
(one or more of MapReduce jobs)

Hive: Behind the Scenes

```
STAGE DEPENDENCIES:
 Stage-1 is a root stage
 Stage-2 depends on stages: Stage-1
 Stage-0 is a root stage


STAGE PLANS:
 Stage: Stage-1
  Map Reduce
   Alias -> Map Operator Tree:
    s
     TableScan
      alias: s
      Filter Operator
       predicate:
         expr: (freq >= 1)
         type: boolean
       Reduce Output Operator
        key expressions:
            expr: word
            type: string
        sort order: +
        Map-reduce partition columns:
            expr: word
            type: string
        tag: 0
        value expressions:
            expr: freq
            type: int
            expr: word
            type: string
    k
     TableScan
      alias: k
      Filter Operator
       predicate:
         expr: (freq >= 1)
         type: boolean
       Reduce Output Operator
        key expressions:
            expr: word
            type: string
        sort order: +
        Map-reduce partition columns:
            expr: word
            type: string
        tag: 1
        value expressions:
            expr: freq
            type: int
   Reduce Operator Tree:
      Join Operator
       condition map:
         Inner Join 0 to 1
       condition expressions:
        0 {VALUE._col0} {VALUE._col1}
        1 {VALUE._col0}
       outputColumnNames: _col0, _col1, _col2
       Filter Operator
        predicate:
          expr: ((_col0 >= 1) and (_col2 >= 1))
          type: boolean
        Select Operator
         expressions:
            expr: _col1
            type: string
            expr: _col0
            type: int
            expr: _col2
            type: int
         outputColumnNames: _col0, _col1, _col2
         File Output Operator
          compressed: false
          GlobalTableId: 0
          table:
            input format: org.apache.hadoop.mapred.SequenceFileInputFormat
            output format: org.apache.hadoop.hive.ql.io.HiveSequenceFileOutputFormat

 Stage: Stage-2
  Map Reduce
   Alias -> Map Operator Tree:
    hdfs://localhost:8022/tmp/hive-training/364214370/10002
      Reduce Output Operator
       key expressions:
          expr: _col1
          type: int
       sort order: -
       tag: -1
       value expressions:
          expr: _col0
          type: string
          expr: _col1
          type: int
          expr: _col2
          type: int
   Reduce Operator Tree:
    Extract
     Limit
      File Output Operator
       compressed: false
       GlobalTableId: 0
       table:
         input format: org.apache.hadoop.mapred.TextInputFormat
         output format: org.apache.hadoop.hive.ql.io.HiveIgnoreKeyTextOutputFormat

 Stage: Stage-0
  Fetch Operator
   limit: 10
```

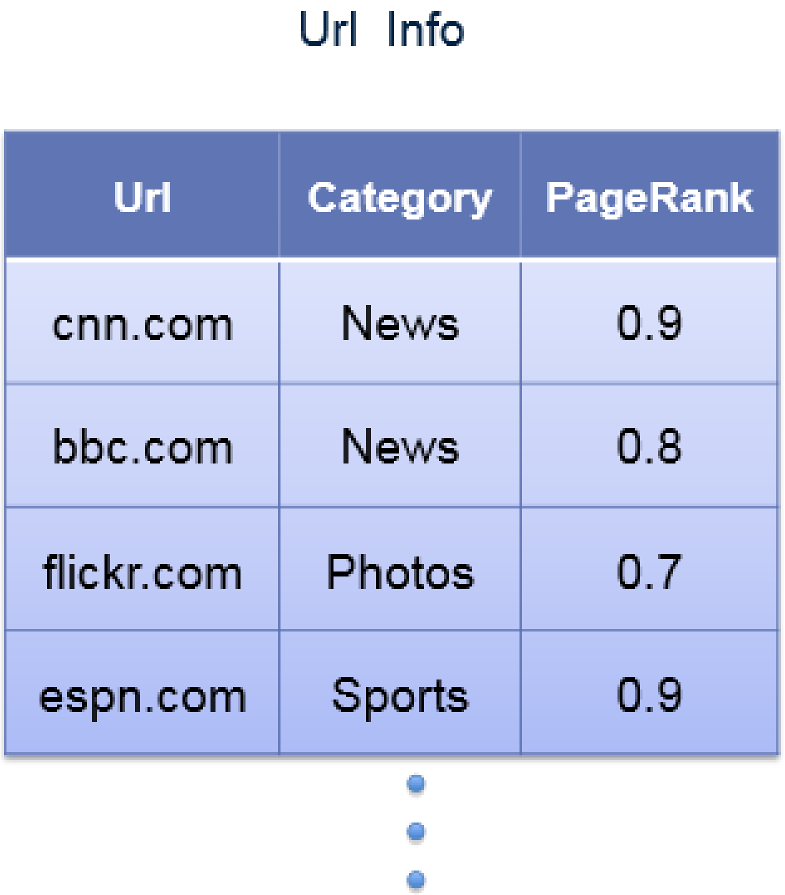
Pig: Example

- Task: Find the top 10 most visited pages in each category



Visits

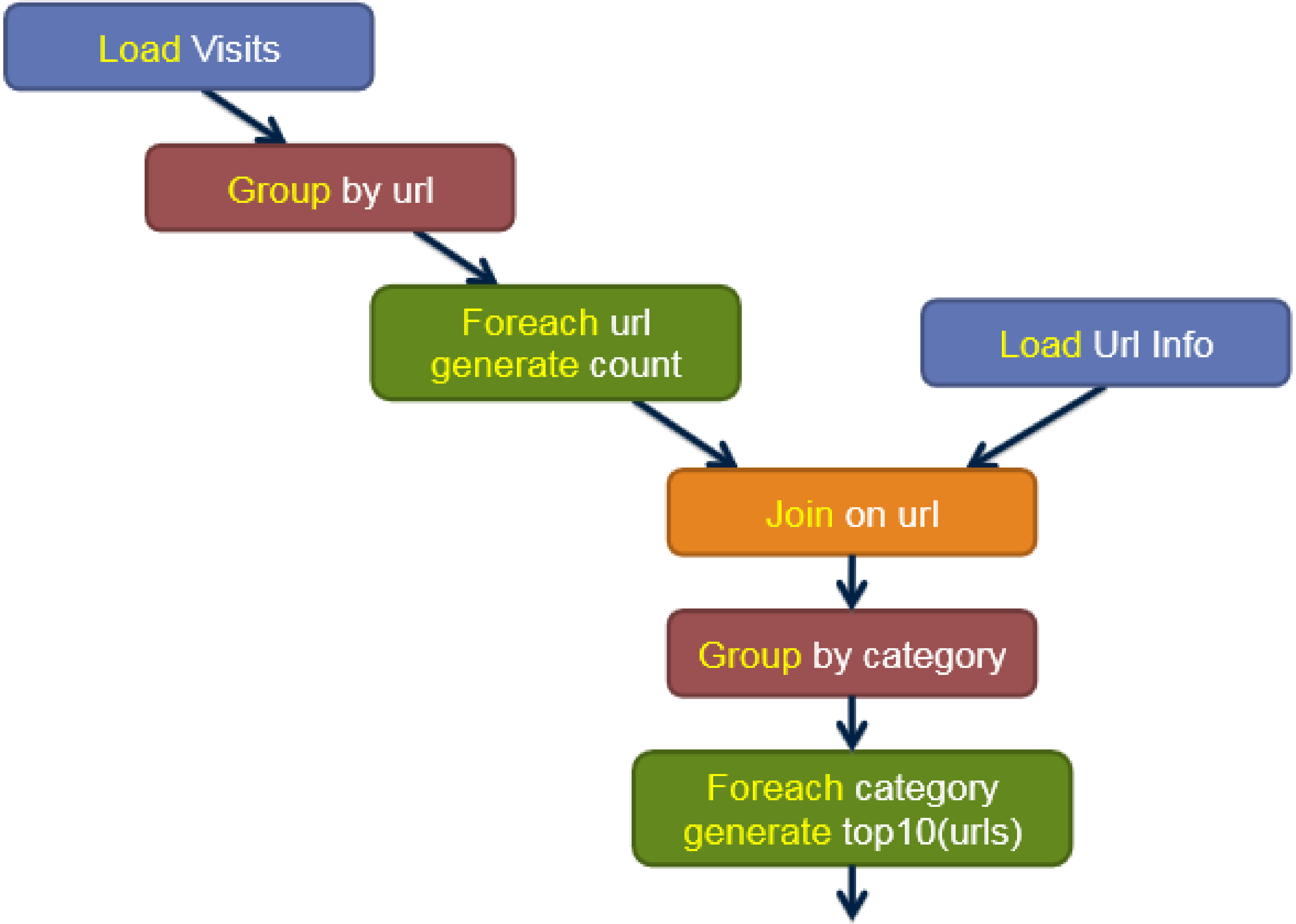
User	Url	Time
Amy	cnn.com	8:00
Amy	bbc.com	10:00
Amy	flickr.com	10:05
Fred	cnn.com	12:00



Url Info

Url	Category	PageRank
cnn.com	News	0.9
bbc.com	News	0.8
flickr.com	Photos	0.7
espn.com	Sports	0.9

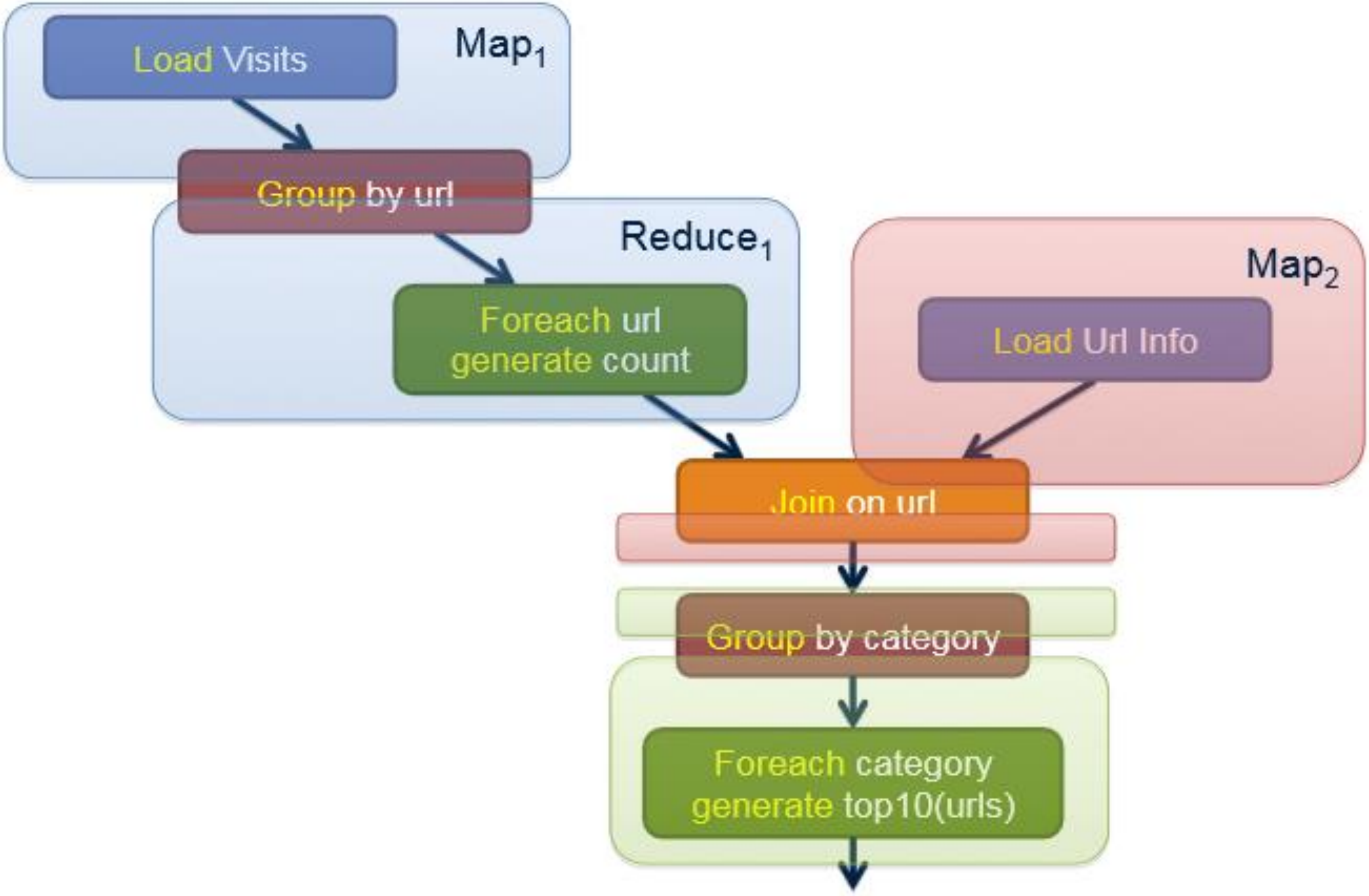
Pig Query Plan



Pig Script

```
visits = load ‘/data/visits’  as (user,  url,  time);
gVisits =  group visits  by url;
visitCounts =  foreach gVisits generate url,  count(visits);
urlInfo =  load ‘/data/urlInfo’  as (url,  category,  pRank);
visitCounts =  join visitCounts by url,  urlInfo by url;
gCategories =  group visitCounts by category;
topUrls =  foreach gCategories generate top(visitCounts,10);

store  topUrls into  ‘/data/topUrls’;
```

Pig Query Plan



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