

CES Data Scientist

Distributed Computing with MapReduce and Beyond





Introduction

The MapReduce Computing Model

MapReduce Optimization

MapReduce in Hadoop

Toward Easier Programming Interfaces: Pig

Limitations of MapReduce

Alternative Distributed Computation Models

5 January 2015





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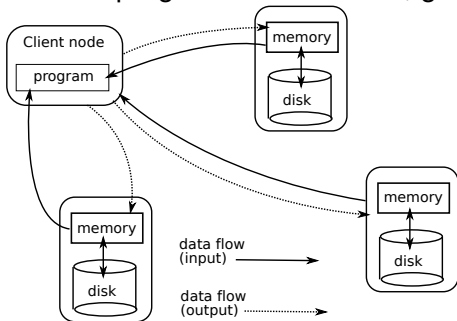


- **Very large** data collections (TB to PB) stored on distributed filesystems:
 - Query logs
 - Search engine indexes
 - Sensor data
- Need **efficient ways** for analyzing, reformatting, processing them
- In particular, we want:
 - Parallelization of computation (benefiting of the processing power of all nodes in a cluster)
 - Resilience to failure

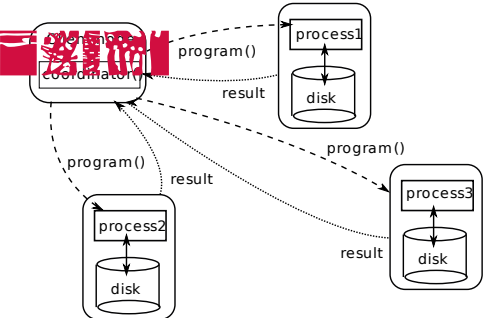




Run the program at client node, get data from the distributed system.



Downsides: important data flows, no use of the cluster computing resources.



- **MapReduce**: A **programming model** (inspired by standard functional programming operators) to facilitate the development and execution of distributed tasks.
- Published by Google Labs in 2004 at OSDI [DG04]. Widely used since then, open-source implementation in **Hadoop**.



- The programmer defines the program logic as **two functions**:
 - Map** transforms the input into key-value pairs to process
 - Reduce** aggregates the list of values for each key
- The MapReduce environment takes in charge **distribution aspects**
- A complex program can be decomposed as a **succession** of Map and Reduce tasks
- Higher-level languages (**Pig**, Hive, etc.) help with writing distributed applications





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1. User-defined: $map : (K, V) \rightarrow list(K', V')$

```
function map(uri, document)
  foreach distinct term in document
    output (term, count(term, document))
```

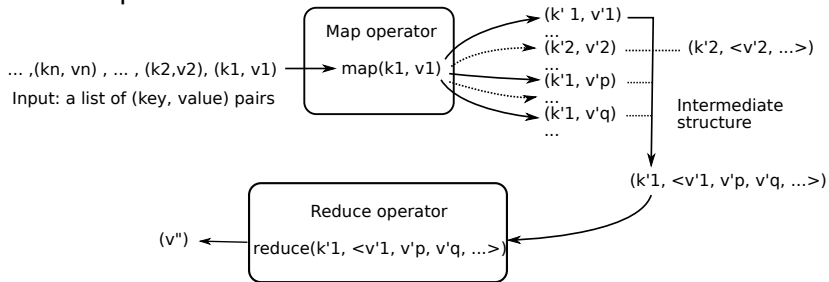
2. Fixed behavior: $shuffle : list(K', V') \rightarrow list(K', list(V'))$ regroups all intermediate pairs on the key
3. User-defined: $reduce : (K', list(V')) \rightarrow list(K'', V'')$

```
function reduce(term, counts)
  output (term, sum(counts))
```





each pair, at each phase, is processed **independently** from the other pairs.



Network and distribution are transparently managed by the MapReduce environment.





| URL | Document |
|-----|----------|
|-----|----------|

- | | |
|-------|--|
| u_1 | the jaguar is a new world mammal of the felidae family. |
| u_2 | for jaguar, atari was keen to use a 68k family device. |
| u_3 | mac os x jaguar is available at a price of us \$199 for apple's new "family pack". |
| u_4 | one such ruling family to incorporate the jaguar into their name is jaguar paw. |
| u_5 | it is a big cat. |
-





count

jaguar 1
mammal 1
family 1
jaguar 1
available 1
jaguar 1
family 1
family 1
jaguar 2

...

map output
shuffle input



| term | count |
|------|-------|
|------|-------|

| | |
|-----------|---|
| jaguar | 1 |
| mammal | 1 |
| family | 1 |
| jaguar | 1 |
| available | 1 |
| jaguar | 1 |
| family | 1 |
| family | 1 |
| jaguar | 2 |
| ... | |

map output
shuffle input

| term | count |
|-----------|---------|
| jaguar | 1,1,1,2 |
| mammal | 1 |
| family | 1,1,1 |
| available | 1 |
| ... | |

shuffle output
reduce input



| | count |
|-----------|-------|
| jaguar | 1 |
| mammal | 1 |
| family | 1 |
| jaguar | 1 |
| available | 1 |
| jaguar | 1 |
| family | 1 |
| family | 1 |
| jaguar | 2 |
| ... | |

map output
shuffle input

| term | count |
|-----------|---------|
| jaguar | 1,1,1,2 |
| mammal | 1 |
| family | 1,1,1 |
| available | 1 |
| ... | |

shuffle output
reduce input

| term | count |
|-----------|-------|
| jaguar | 5 |
| mammal | 1 |
| family | 3 |
| available | 1 |
| ... | |

final output





```
function map(uri, document)
  foreach distinct term in document
    output (term, count(term, document))
```

can actually be further simplified:

```
function map(uri, document)
  foreach term in document
    output (term, 1)
```

since all counts are aggregated.

Might be less efficient though (we may need a **combiner**, see further)





Nodes inside a MapReduce cluster are decomposed as follows:

- A **jobtracker** acts as a master node; MapReduce jobs are submitted to it
- Several **tasktrackers** run the computation itself, i.e., *map* and *reduce* tasks
- A given tasktracker may run several tasks in parallel
- Tasktrackers usually also act as **data nodes** of a distributed filesystem (e.g., GFS, HDFS)

+ a client node where the application is launched.



A **MapReduce job** takes care of the distribution, synchronization and failure handling. Specifically:

- the input is split into M groups; each group is assigned to a **mapper** (assignment is based on the data locality principle)
- each mapper processes a group and stores the intermediate pairs locally
- grouped instances are assigned to **reducers** thanks to a hash function
- (*shuffle*) intermediate pairs are sorted on their key by the reducer
- one obtains grouped instances, submitted to the *reduce* function

Remark: the data locality does no longer hold for the *reduce* phase, since it reads from the mappers.

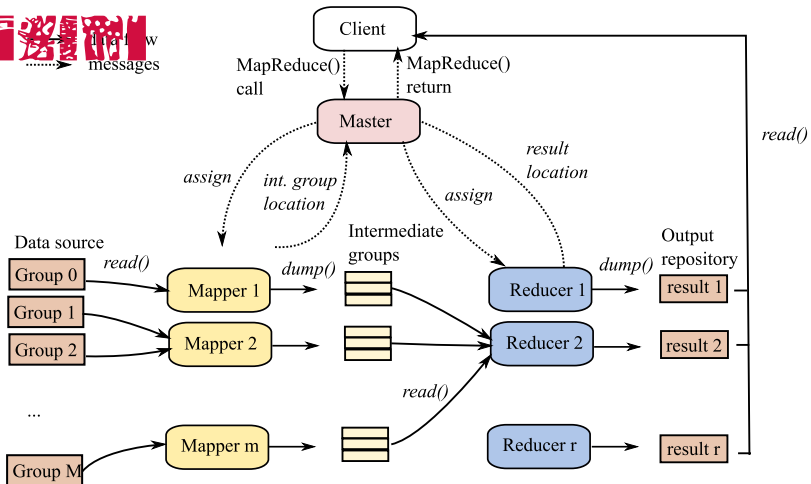




Each mapper task processes **a fixed amount of data (split)**, usually set to the distributed filesystem block size (e.g., 64MB)

- The number of mapper nodes is function of the number of mapper tasks and the number of available nodes in the cluster: each mapper nodes can process (in parallel and sequentially) **several mapper tasks**
- Assignment to mapper tries optimizing **data locality**: the mapper node in charge of a split is, if possible, one that stores a replica of this split (or if not possible, a node of the same rack)
- The number of reducer tasks is **set by the user**
- Assignment to reducers is done through a hashing of the key, usually **uniformly at random**; no data locality possible







Let the input consists of documents, say, one million 100-terms documents of approximately 1 KB each.

The split operation distributes these documents in groups of 64 MBs: each group consist of 64,000 documents. Therefore $M = \lceil 1,000,000/64,000 \rceil \approx 16,000$ groups.

If there are 1,000 mapper node, each node processes on average 16 splits.

If there are 1,000 reducers, each reducer r_i processes all key-value pairs for terms t such that $hash(t) = i$ ($1 \leq i \leq 1,000$)



Assume that $hash('call') = hash('mine') = hash('blog') = i = 100$. We focus on three Mappers m_p , m_q and m_r :

1. $G_j^p = (j \dots, ('mine', 1), \dots, ('call', 1), \dots, ('mine', 1), \dots, ('blog', 1), \dots, j)$
2. $G_j^q = (j \dots, ('call', 1), \dots, ('blog', 1), \dots, j)$
3. $G_j^r = (j \dots, ('blog', 1), \dots, ('mine', 1), \dots, ('blog', 1), \dots, j)$

r_i reads G_j^p , G_j^q and G_j^r from the three Mappers, sorts their unioned content, and groups the pairs with a common key:

$\dots, ('blog', j1, 1, 1, 1j), \dots, ('call', j1, 1j), \dots, ('mine', j1, 1, 1j)$

Our *reduce* function is then applied by r_i to each element of this list. The output is $('blog', 4)$, $('call', 2)$ and $('mine', 3)$

In case of failure, because the tasks are distributed over hundreds or thousands of machines, the chances that a problem occurs somewhere are much larger; starting the job from the beginning is not a valid option.

The Master periodically checks the availability and reachability of the tasktrackers (**heartbeats**) and whether *map* or *reduce* jobs make any **progress**

1. if a reducer fails, its task is **reassigned to another tasktracker**; this usually requires restarting mapper tasks as well (to produce intermediate groups)
2. if a mapper fails, its task is **reassigned to another tasktracker**
3. if the jobtracker fails, **the whole job should be re-initiated**





Two datasets, A and B that we need to join for a MapReduce task

- If one of the dataset is small, it can be **sent over fully** to each tasktracker and exploited inside the *map* (and possibly *reduce*) functions
- Otherwise, each dataset should be **grouped according to the join key**, and the result of the join can be computing in the *reduce* function

Not very convenient to express in MapReduce. Much easier using Pig.





■ Prefer:

- **Simple** *map* and *reduce* functions
- Mapper tasks processing **large data chunks** (at least the size of distributed filesystem blocks)
- A given application may have:
 - **A chain of *map* functions** (input processing, filtering, extraction. . .)
 - A sequence of **several *map-reduce jobs***
 - **No *reduce task*** when everything can be expressed in the *map* (zero reducers, or the identity reducer function)
- Not the right tool for everything(see further)





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5 January 2015



■ A mapper task can produce a large number of pairs with the same key

- They need to be sent over the network to the reducer: **costly**
- It is often possible to **combine** these pairs into a single key-value pair

Example

(jaguar,1), (jaguar, 1), (jaguar, 1), (jaguar, 2) → (jaguar, 5)

- *combiner* : $\text{list}(V') \rightarrow V'$ function executed (possibly several times) to **combine the values for a given key**, on a mapper node
- No guarantee that the *combiner* is called
- Easy case: the combiner is the same as the *reduce* function. Possible when the aggregate function α computed by *reduce* is **distributive**: $\alpha(k_1, \alpha(k_2, k_3)) = \alpha(k_1, k_2, k_3)$





- **Data transfers** over the network:
 - From datanodes to mapper nodes (usually reduced using data locality)
 - From mappers to reducers
 - From reducers to datanodes to store the final output
- Each of these can benefit from **data compression**
- **Tradeoff** between volume of data transfer and (de)compression time
- Usually, **compressing *map outputs*** using a fast compressor increases efficiency





- Sorting of pairs on each reducer, to compute the groups: **costly operation**
- Sorting much more efficient **in memory** than on disk
- **Increasing the amount of memory** available for *shuffle* operations can greatly increase the performance
- ... at the downside of less memory available for *map* and *reduce* tasks (but usually not much needed)





- The MapReduce jobtracker tries detecting tasks that take longer than usual (e.g., because of hardware problems)
- When detected, such a task is **speculatively** executed on another tasktracker, without killing the existing task
- Eventually, when one of the attempts succeeds, the other one is killed





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5 January 2015





Open source software, Java-based, managed by the Apache foundation, for **large-scale distributed storage and computing**

- Originally developed for Apache Nutch (open-source Web search engine), a part of Apache Lucene (text indexing platform)
- Open-source implementation of GFS and Google's MapReduce
- Yahoo!: a main contributor of the development of Hadoop
- Hadoop components:
 - Hadoop filesystem (HDFS)
 - MapReduce
 - Pig (data exploration), Hive (data warehousing): higher-level languages for describing MapReduce applications
 - HBase: column-oriented distributed DBMS
 - ZooKeeper: coordination service for distributed applications





- Different APIs to write Hadoop programs:
 - A rich **Java** API (main way to write Hadoop programs)
 - A **Streaming** API that can be used to write *map* and *reduce* functions in any programming language (using standard inputs and outputs)
 - A **C++** API (Hadoop Pipes)
 - With a **higher-language level** (e.g., Pig, Hive)
- Advanced features only available in the Java API
- Two different Java APIs depending on the Hadoop version; presenting the “old” one



```
public class TermCountMapper extends MapReduceBase
implements Mapper<Text,Text,Text,IntWritable> {
public void map(
    Text uri, Text document,
    OutputCollector<Text, IntWritable> output,
    Reporter reporter)
{
    Pattern p=Pattern.compile("[\\p{L}]+");
    Matcher m=p.matcher(document);
    while(matcher.find()) {
        String term=matcher.group().
        output.collect(new Text(term),new IntWritable(1));
    }
}
}
```





```
public class TermCountReducer extends MapReduceBase
implements Reducer<Text,IntWritable,Text,IntWritable>
public void reduce(
    Text term, Iterator<IntWritable> counts,
    OutputCollector<Text, IntWritable> output,
    Reporter reporter)
{
    int sum=0;
    while(counts.hasNext()) {
        sum+=values.next().get();
    }
    output.collect(term, new IntWritable(sum));
}
}
```



```
public class TermCount {
    public static void main(String args[]) throws IOException {
        JobConf conf = new JobConf(TermCount.class);
        FileInputFormat.addInputPath(conf, new Path(args[0]));
        FileOutputFormat.addOutputPath(conf, new Path(args[1]));

        // In a real application, we would have a custom input
        // format to fetch URI-document pairs
        conf.setInputFormat(KeyValueTextInputFormat.class);

        conf.setMapperClass(TermCountMapper.class);
        conf.setCombinerClass(TermCountReducer.class);
        conf.setReducerClass(TermCountReducer.class);

        conf.setOutputKeyClass(Text.class);
        conf.setOutputValueClass(IntWritable.class);

        JobClient.runJob(conf);
    }
}
```

Required environment:

JDK on client

- JRE on all Hadoop nodes
- Hadoop distribution (HDFS + MapReduce) on client and all Hadoop nodes
- SSH servers on each tasktracker, SSH client on jobtracker (used to control the execution of tasktrackers)
- An IDE (e.g., Eclipse + plugin) on client

■ Three different execution modes:

local One mapper, one reducer, run locally from the same JVM as the client

pseudo-distributed mappers and reducers are launched on a single machine, but communicate over the network

distributed over a cluster for real runs





- Easiest: debugging in **local mode**
- **Web interface** with status information about the job
- **Standard output and error** channels saved on each node, accessible through the Web interface
- **Counters** can be used to track side information across a MapReduce job (e.g., number of invalid input records)
- **Remote debugging** possible but complicated to set up (impossible to know in advance where a *map* or *reduce* task will be executed)
- **IsolationRunner** allows to run in isolation part of the MapReduce job





- By default, each *map* and *reduce* task (of a given split) is run in a **separate JVM**
- When there is a lot of initialization to be done, or when splits are small, might be useful to **reuse JVMs** for subsequent tasks
- Of course, only works for tasks run on the same node





- Possibly to set up one's own Hadoop cluster
- But often easier to use clusters in the cloud that support MapReduce:
 - Amazon EC2
 - Cloudera
 - etc.
- Not always easy to know the cluster's configuration (in terms of racks, etc.) when on the cloud, which hurts data locality in MapReduce



Toward Easier Programming Interfaces: Pig

Basics

Pig operators

From Pig to MapReduce

Limitations of MapReduce

Alternative Distributed Computation Models



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Motivation define high-level languages that use MapReduce as an underlying data processor.

A Pig Latin statement is an operator that takes a relation as input and produces another relation as output.

Pig Latin statements are generally organized in the following manner:

1. A `LOAD` statement reads data from the file system as a *relation* (list of tuples).
2. A series of “transformation” statements process the data.
3. A `STORE` statement writes output to the file system; or, a `DUMP` statement displays output to the screen.

Statements are executed as composition of MapReduce jobs.





- Part of Hadoop, downloadable from the Hadoop Web site
- Interactive interface (Grunt) and batch mode
- Two execution modes:
 - local** data is read from disk, operations are directly executed, no MapReduce
 - MapReduce** on top of a MapReduce cluster (pipeline of MapReduce jobs)





```
a = load 'hdfs://input.txt' as (line: chararray);  
b = foreach a generate flatten(TOKENIZE(line)) as word;  
c = group b by word;  
d = foreach c generate COUNT(b), group;  
dump d;
```






A flat file, tab-separated, extracted from DBLP.

| | | |
|------|---------------|---|
| 2005 | VLDB J. | Model-based approximate querying in sensor networks. |
| 1997 | VLDB J. | Dictionary-Based Order-Preserving String Compression. |
| 2003 | SIGMOD Record | Time management for new faculty. |
| 2001 | VLDB J. | E-Services - Guest editorial. |
| 2003 | SIGMOD Record | Exposing undergraduate students to database system inte |
| 1998 | VLDB J. | Integrating Reliable Memory in Databases. |
| 1996 | VLDB J. | Query Processing and Optimization in Oracle Rdb |
| 1996 | VLDB J. | A Complete Temporal Relational Algebra. |
| 1994 | SIGMOD Record | Data Modelling in the Large. |
| 2002 | SIGMOD Record | Data Mining: Concepts and Techniques - Book Review. |





```
add records from the file
articles = load 'journal.txt'
  as (year: chararray, journal: chararray,
      title: chararray) ;

sr_articles = filter articles
  by journal=='SIGMOD Record';

year_groups = group sr_articles by year;

avg_nb = foreach year_groups
  generate group, count(sr_articles.title);

dump avg_nb;
```



The model allows nesting of bags and tuples. Example: the `year_group` temporary bag.

```
group: 1990
sr_articles:
{
  (1990, SIGMOD Record, SQL For Networks of Relations.),
  (1990, SIGMOD Record, New Hope on Data Models and Types.)
}
```

Unlimited nesting, but no references, no constraint of any kind (for parallelization purposes).





Pig allows the representation of heterogeneous data, in the spirit of semi-structured data models (e.g., XML).

The following is a bag with heterogeneous tuples.

```
{  
  (2005, {'SIGMOD Record', 'VLDB J.'},  
         {'article1', 'article2'})  
  (2003, 'SIGMOD Record', {'article1', 'article2'},  
         {'author1', 'author2'})  
}
```



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| | |
|----------|--|
| foreach | Apply one or several expression(s) to each of the input tuples |
| filter | Filter the input tuples with some criteria |
| distinct | Remove duplicates from an input |
| join | Join of two inputs |
| group | Regrouping of data |
| cogroup | Associate two related groups from distinct inputs |
| cross | Cross product of two inputs |
| order | Order an input |
| limit | Keep only a fixed number of elements |
| union | Union of two inputs (note: no need to agree on a same schema, as in SQL) |
| split | Split a relation based on a condition |



Example of a file with tab-separated fields.

| | | |
|------|--------------------------|-----------|
| 1995 | Foundations of Databases | Abiteboul |
| 1995 | Foundations of Databases | Hull |
| 1995 | Foundations of Databases | Vianu |
| 2010 | Web Data Management | Abiteboul |
| 2010 | Web Data Management | Manolescu |
| 2010 | Web Data Management | Rigaux |
| 2010 | Web Data Management | Rousset |
| 2010 | Web Data Management | Senellart |

NB: Pig accepts inputs from user-defined function, written in Java – allows to extract data from any source.



The “program”:

```
books = load 'webdam-books.txt'
  as (year: int, title: chararray, author: chararray)
group_auth = group books by title;
authors = foreach group_auth
  generate group, books.author;
dump authors;
```

and the result:

```
(Foundations of Databases,
  {(Abiteboul),(Hull),(Vianu)})
(Web Data Management,
  {(Abiteboul),(Manolescu),(Rigaux),(Rousset),(Senellart)})
```



Flatten serves to unnest a nested field.

```
-- Take the 'authors' bag and flatten the nested set  
flattened = foreach authors  
  generate group, flatten(author);
```

Applied to the previous authors bags, one obtains:

(Foundations of Databases,Abiteboul)

(Foundations of Databases,Hull)

(Foundations of Databases,Vianu)

(Web Data Management,Abiteboul)

(Web Data Management,Manolescu)

(Web Data Management,Rigaux)

(Web Data Management,Rousset)

(Web Data Management,Senellart)





Allows to gather two data sources in nested fields

Example: a file with publishers:

| | | |
|-------------------------|----------------------------|--------|
| Fundations of Databases | Addison-Wesley | USA |
| Fundations of Databases | Vuibert | France |
| Web Data Management | Cambridge University Press | USA |

The program:

```
publishers = load 'webdam-publishers.txt'  
  as (title: chararray, publisher: chararray) ;  
cogrouped = cogroup flattened by group,  
  publishers by title;
```





For each grouped field value, two nested sets, coming from both sources.

```
(Foundations of Databases,  
  { (Foundations of Databases,Abiteboul),  
    (Foundations of Databases,Hull),  
    (Foundations of Databases,Vianu)  
  },  
  {(Foundations of Databases,Addison-Wesley),  
   (Foundations of Databases,Vuibert)  
  }  
)
```

A kind of join? Yes, at least a preliminary step.



Same as before, but produces a flat output (cross product of the inner nested bags). The nested model is usually more elegant and easier to deal with.

```
-- Take the 'flattened' bag, join with 'publishers'  
joined = join flattened by group, publishers by title;
```

```
(Foundations of Databases,Abiteboul,  
    Foundations of Databases,Addison-Wesley)  
(Foundations of Databases,Abiteboul,  
    Foundations of Databases,Vuibert)  
(Foundations of Databases,Hull,  
    Foundations of Databases,Addison-Wesley)  
(Foundations of Databases,Hull,  
    ...
```



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Limitations of MapReduce

Alternative Distributed Computation Models





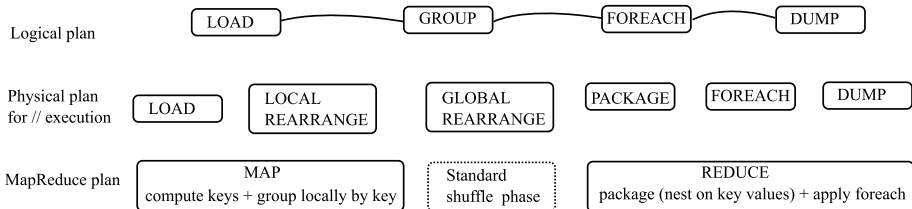
- A Pig program describes a **logical data flow**
- This is implemented with a **physical plan**, in terms of grouping or nesting operations
- This is in turn (for MapReduce execution) implemented using a **sequence of *map* and *reduce* steps**





- Local Rearrange** group tuples with the same key, on a local machine
- Global Rearrange** group tuples with the same key, globally on a cluster
- Package** construct a nested tuple from tuples that have been grouped





```
-- Load books, but keep only books from Victor Vianu
books = load 'webdam-books.txt'
      as (year: int, title: chararray, author: chararray)
vianu = filter books by author == 'Vianu';

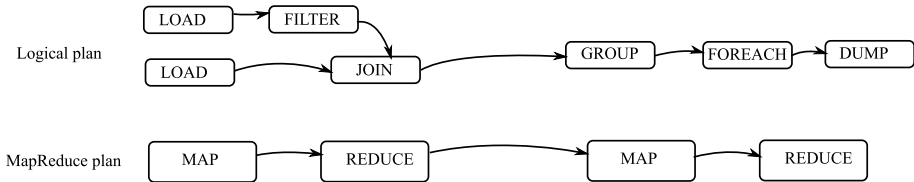
publishers = load 'webdam-publishers.txt'
           as (title: chararray, publisher: chararray) ;

-- Join on the book title
joined = join vianu by title, publishers by title;

-- Now, group on the author name
grouped = group joined by vianu::author;

-- Finally count the publishers
-- (nb: we should remove duplicates!)
count = foreach grouped
         generate group, COUNT(joined.publisher);
```







MapReduce

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- **High latency.** Launching a MapReduce job has a high overhead, and *reduce* functions are only called after all *map* functions succeed, not suitable for applications needing a quick result.
- **Batch processing only.** MapReduce excels at processing a large collection, not at retrieving individual items from a collection.
- **Write-once, read-many mode.** No real possibility of updating a dataset using MapReduce, it should be regenerated from scratch
- **No transactions.** No concurrency control at all, completely unsuitable for transactional applications [PPR⁺09].





- **Relatively low-level.** Ongoing efforts for more high-level languages: Scope [CJL⁺08], Pig [ORS⁺08, GNC⁺09], Hive [TSJ⁺09], Cascading <http://www.cascading.org/>
- **No structure.** Implies lack of indexing, difficult to optimize, etc. [DS87]
- **Hard to tune.** Number of reducers? Compression? Memory available at each node? etc.





- Best of both worlds?
 - DBMS are good at transactions, point queries, structured data
 - MapReduce is good at scalability, batch processing, key-value data
- **HadoopDB** [ABPA⁺09]: standard relational DBMS at each node of a cluster, MapReduce allows communication between nodes
- Possible to use DBMS inputs natively in Hadoop, but no control about data locality





- Multiple jobs concurrently submitted to the MapReduce jobtracker
- Fair scheduling required:
 - each submitted job should have some share of the cluster
 - prioritization of jobs
 - long-standing jobs should not block quick jobs
 - fairness with respect to users
- Standard Hadoop scheduler: priority queue
- Hadoop Fair Scheduler: ensures cluster resources are shared among users. Preemption (= killing running tasks) possible in case the sharing becomes unbalanced.





MapReduce is a simple model for **batch processing** of very large collections.

⇒ **good** for data analytics; **not good** for point queries (high latency).

The systems brings **robustness against failure** of a component and **transparent distribution and scalability**.

⇒ more expressive languages required (Pig)





- Original description of the MapReduce framework [DG04]
- Hadoop distribution and documentation available at <http://hadoop.apache.org/>
- Documentation for Pig is available at <http://wiki.apache.org/pig/>
- Excellent textbook on Hadoop [Whi09]
- Online MapReduce exercises with validation <http://cloudcomputing.ruc.edu.cn/login/login.jsp>



Toward Easier Programming Interfaces: Pig

Limitations of MapReduce

Alternative Distributed Computation Models

Apache Hive: SQL Analytics on MapReduce

Apache Storm: Real-Time Computation

Apache Spark: More Complex Workflows

Pregel, Apache Giraph, GraphLab: Think as a Vertex

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- Data warehousing on top of Hadoop
- SQL-like language to express high-level queries, esp., aggregate and analytics
- Queries translated into Map–Reduce jobs (or Spark jobs, see further)
- Similar as Pig, but declarative vs imperative, and geared towards analytics vs transformation of datasets; dataflow more obvious in Pig programs





```
CREATE TABLE doc(text STRING)
ROW FORMAT DELIMITED FIELDS TERMINATED BY '\n'
STORED AS TEXTFILE;

LOAD DATA INPATH 'hdfs://input.txt' INTO TABLE doc;

SELECT word, COUNT(*)
FROM doc LATERAL VIEW EXPLODE(SPLIT(text, ' ')) temp
  AS word
GROUP BY word;
```



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- Real-time analytics, in opposition to the batch model of MapReduce
- Achieves very reasonable latency
- Process data in a streaming fashion
- Based on the notion of event producer (spout) and manipulation (bolt)
- Written in Clojure (Lisp) + Java, jobs usually written in Java



```

public class TCStorm {
    public static void main(String[] args) throws Exception {
        Config config = new Config();
        config.put("inputFile", args[0]);
        TopologyBuilder builder = new TopologyBuilder();
        builder.setSpout("line-reader-spout",
            new LineReaderSpout());
        builder.setBolt("word-spitter", new WordSplitterBolt()).
            shuffleGrouping("line-reader-spout");
        builder.setBolt("word-counter", new WordCounterBolt()).
            shuffleGrouping("word-spitter");
        LocalCluster cluster = new LocalCluster();
        cluster.submitTopology("HelloStorm", config,
            builder.createTopology());
    }
}

```

Only the driver, the spouts and the bolts also need to be defined!

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■ Similar positioning as Pig: high-level language with a dataflow of operators

- Many more operators than Pig
- Complex programs can be written in Scala, Java, or Python
- Contrarily to Pig, jobs are not translated to MapReduce, but executed directly in a distributed fashion
- Based on **RDDs** (Resilient Distributed Dataset) that can be HDFS files, HBase tables, or the result of applying a succession of operators on these
- Contrarily to MapReduce, local workers have the ability to keep data in memory in a succession of tasks
- Extensions allowing to perform streaming data processing, to process Hive SQL queries
- MLLib: machine learning library on top of Spark





```
file = spark.textFile("hdfs://input.txt")
counts = file.flatMap(lambda line: line.split(" ")) \
    .map(lambda word: (word, 1)) \
    .reduceByKey(lambda a, b: a + b)
counts.saveAsTextFile("hdfs://output.txt")
```



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Parallel computation on graph-like data (Web graph, social networks, transportation networks, etc.)

- Pregel: original system by Google
- Apache Giraph: open-source clone of Pregel
- GraphLab: similar goals, different architecture
- One writes **vertex programs**: each vertex receives messages and sends messages to its neighbours
- Pregel and Giraph are based on the **bulk synchronous parallel** paradigm: synchronization barrier once vertex programs are executed on every vertex
- GraphLab uses an **asynchronous** model



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