

Lecture 2: Spark RDD, DataFrame, ML Pipelines, and Parallelization

COM6012 Scalable Machine Learning

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Week 2 Objectives

1. Describe the key features and differences between **Resilient Distributed Datasets (RDDs)** and **DataFrames** in Apache Spark.
2. Identify the components of **Spark Machine Learning Pipelines** and utilize PySpark MLlib to construct, train, and evaluate machine learning models.
3. Explain the concept of **Directed Acyclic Graphs (DAG)** in Spark and their role in task **execution** and **parallelization** within Spark programs.

Contents

- **Resilient Distributed Datasets**

- DataFrames and Datasets

- Machine Learning Pipelines

- Execution Parallelization

Spark SQL and
DataFrames

Pandas API on
Spark

Structured
Streaming

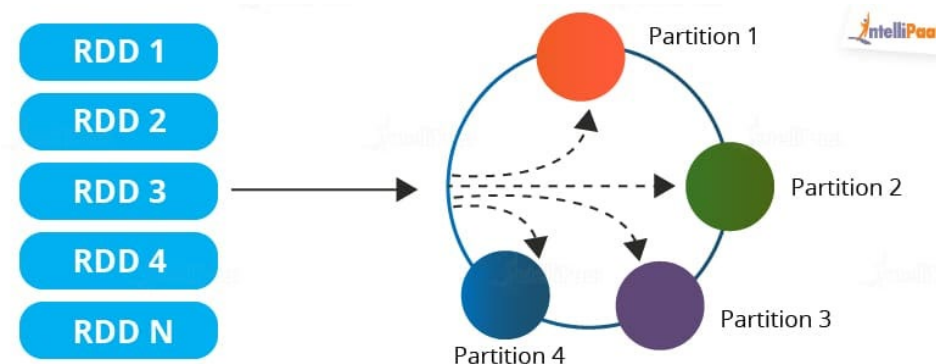
Machine
Learning
MLlib

Spark Core and **RDDs**

<https://spark.apache.org/docs/latest/api/python/index.html>

RDD

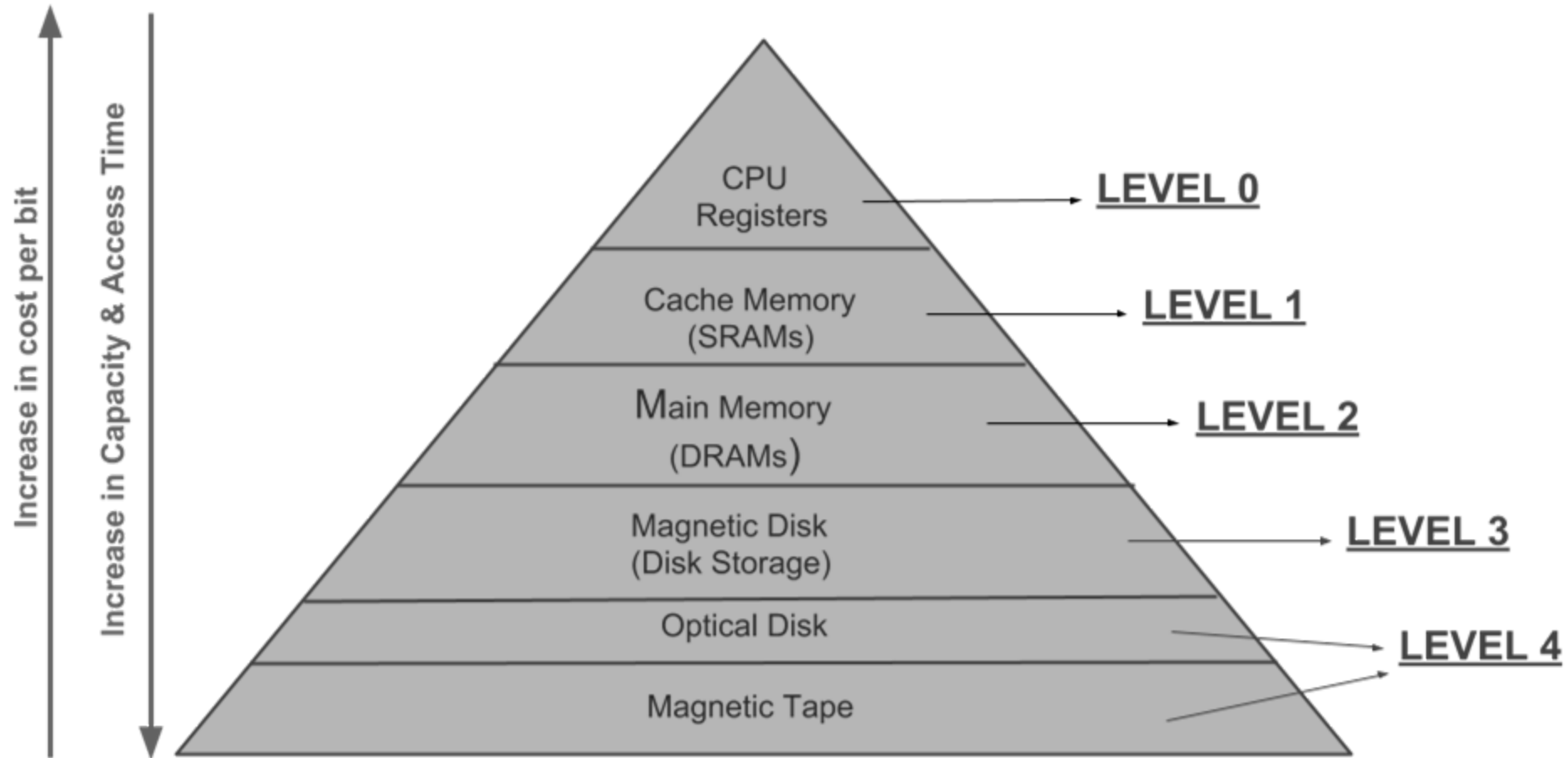
- Resilient Distributed Datasets
 - A **distributed** memory abstraction enabling **in-memory** computations on large **clusters** in a **fault-tolerant** manner
 - The **primary** data abstraction in Spark enabling operations on collection of elements in parallel
- **R**: recompute missing partitions due to node **failures**
- **D**: data **distributed** on multiple nodes in a cluster
- **D**: a collection of **partitioned** elements (**datasets**)



RDD Traits

- **In-Memory**: data inside RDD is stored in memory as much (size) and long (time) as possible
- **Immutable (read-only)**: no change after creation, only transformed using transformations to new RDDs
- **Lazily evaluated**: RDD data not available/transformed until an action is executed that triggers the execution
- **Parallel**: process data in parallel
- **Partitioned**: the data in a RDD is partitioned and then distributed across nodes in a cluster
- **Cacheable**: hold all the data in a persistent "storage" like memory (the most preferred) or disk (the least preferred)

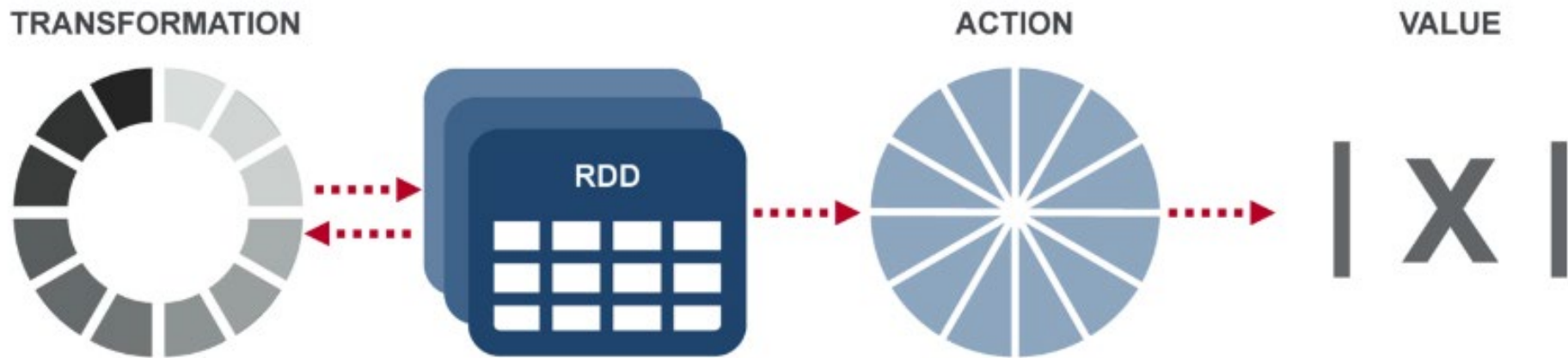
Computer Memory Hierarchy



[Memory Hierarchy Design and its Characteristics - GeeksforGeeks](#)

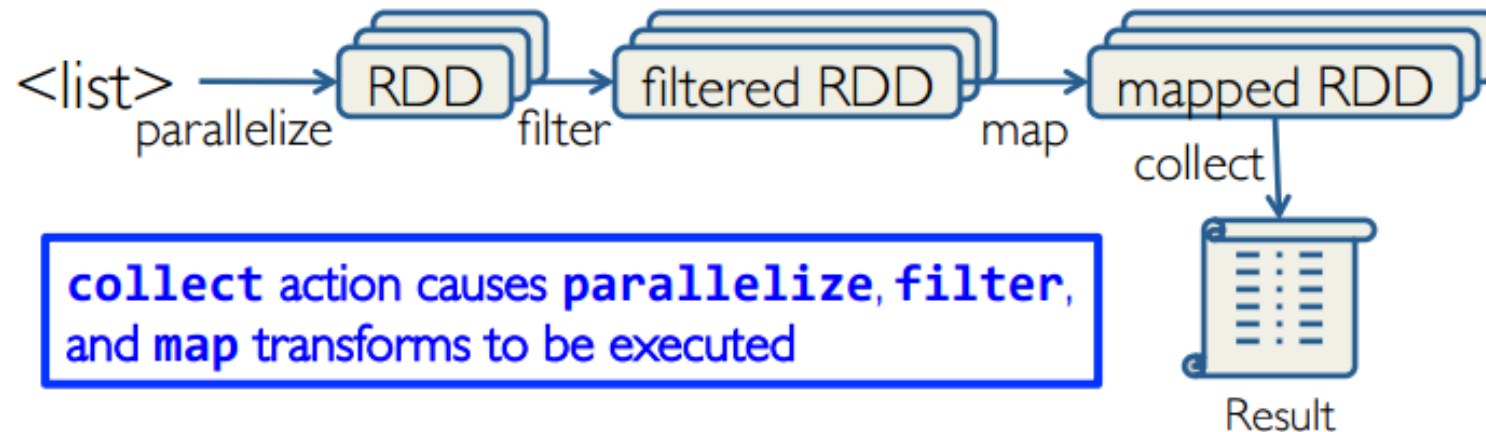
RDD Operations

- **Transformation**: takes an RDD and returns a new RDD but nothing gets evaluated / computed
- **Action**: **all** the data processing queries are **computed** (evaluated) and the result value is returned



RDD Workflow

- Create an RDD from a data source, e.g. RDD or file
- Apply transformations to an RDD, e.g., map, filter
- Apply actions to an RDD, e.g., collect, count
- Users to control 1) persistence, 2) partitioning



Creating RDDs

- Parallelize existing Python collections (lists)
- Transform existing RDDs
- Create from (HDFS, text, Amazon S3) files
- sc APIs: `sc.parallelize`, `sc.hadoopFile`, `sc.textFile`



Parallelized
Collections

From RDDs

External
Data

Spark Transformations

- Create new datasets from an existing one
- Lazy evaluation: just **remember** transformations applied to the base dataset (results not computed)
 - Spark optimizes the required calculations
 - Spark recovers from failures

Transformation	Meaning
map (<i>func</i>)	Return a new distributed dataset formed by passing each element of the source through a function <i>func</i> .
filter (<i>func</i>)	Return a new dataset formed by selecting those elements of the source on which <i>func</i> returns true.
flatMap (<i>func</i>)	Similar to map, but each input item can be mapped to 0 or more output items (so <i>func</i> should return a Seq rather than a single item).
mapPartitions (<i>func</i>)	Similar to map, but runs separately on each partition (block) of the RDD, so <i>func</i> must be of type <code>Iterator<T> => Iterator<U></code> when running on an RDD of type T.

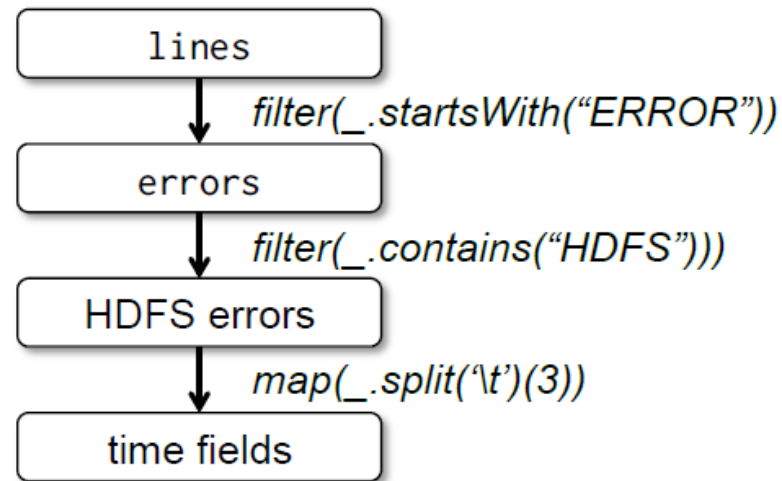
Spark Actions

- Cause Spark to execute recipe to transform source
- Mechanism for getting results out of Spark

Action	Meaning
reduce (<i>func</i>)	Aggregate the elements of the dataset using a function <i>func</i> (which takes two arguments and returns one). The function should be commutative and associative so that it can be computed correctly in parallel.
collect ()	Return all the elements of the dataset as an array at the driver program. This is usually useful after a filter or other operation that returns a sufficiently small subset of the data.
count ()	Return the number of elements in the dataset.
first ()	Return the first element of the dataset (similar to <code>take(1)</code>).
take (<i>n</i>)	Return an array with the first <i>n</i> elements of the dataset.
takeSample (<i>withReplacement</i> , <i>num</i> , [<i>seed</i>])	Return an array with a random sample of <i>num</i> elements of the dataset, with or without replacement, optionally pre-specifying a random number generator seed.
takeOrdered (<i>n</i> , [<i>ordering</i>])	Return the first <i>n</i> elements of the RDD using either their natural order or a custom comparator.

Example from the [Spark Paper](#) (2012)

- Web service is experiencing errors. Operators want to search terabytes of logs in the Hadoop file system to find the cause.



Lineage Graph

- Line1**: create RDD from an HDFS file (but **NOT** loaded in memory)
- Line3**: ask for errors to persist in memory (when loaded)

Code in Scala

//base RDD

```
val lines = sc.textFile("hdfs://...")
```

//Transformed RDD

```
val errors = lines.filter(_.startsWith("Error"))
```

```
errors.persist() //or .cache()
```

```
errors.count()
```

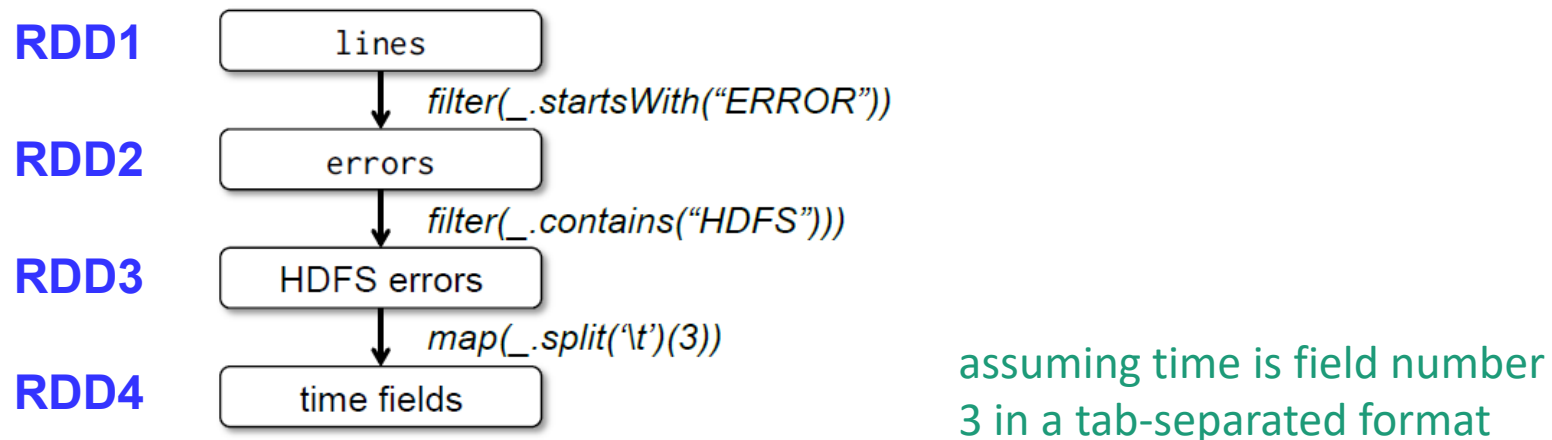
```
errors.filter(_.contains("HDFS"))
```

```
.map(_.split("\\t")(3))
```

```
.collect()
```

Lineage Graph → Fault-Tolerance

- RDDs keep track of **lineage** → how it was derived, how to compute its partitions from data in **stable** storage
- A partition of errors is lost → rebuild it by applying a filter on **only** the corresponding partition of lines → partitions can be recomputed in parallel on different nodes without rolling back the **whole** program

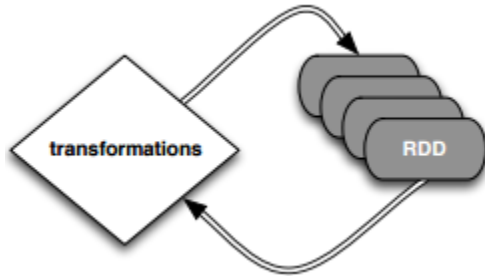


Operations – Step by Step



//base RDD

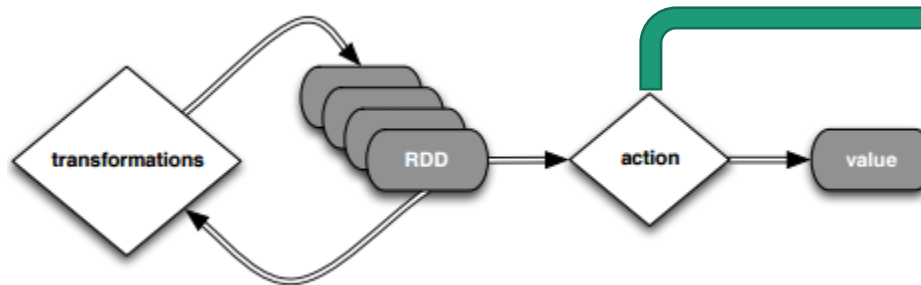
val lines = sc.textFile("hdfs://...")



//Transformed RDD

val errors = lines.filter(_.startsWith("Error"))

errors.persist()



errors.count()

count() causes Spark to:

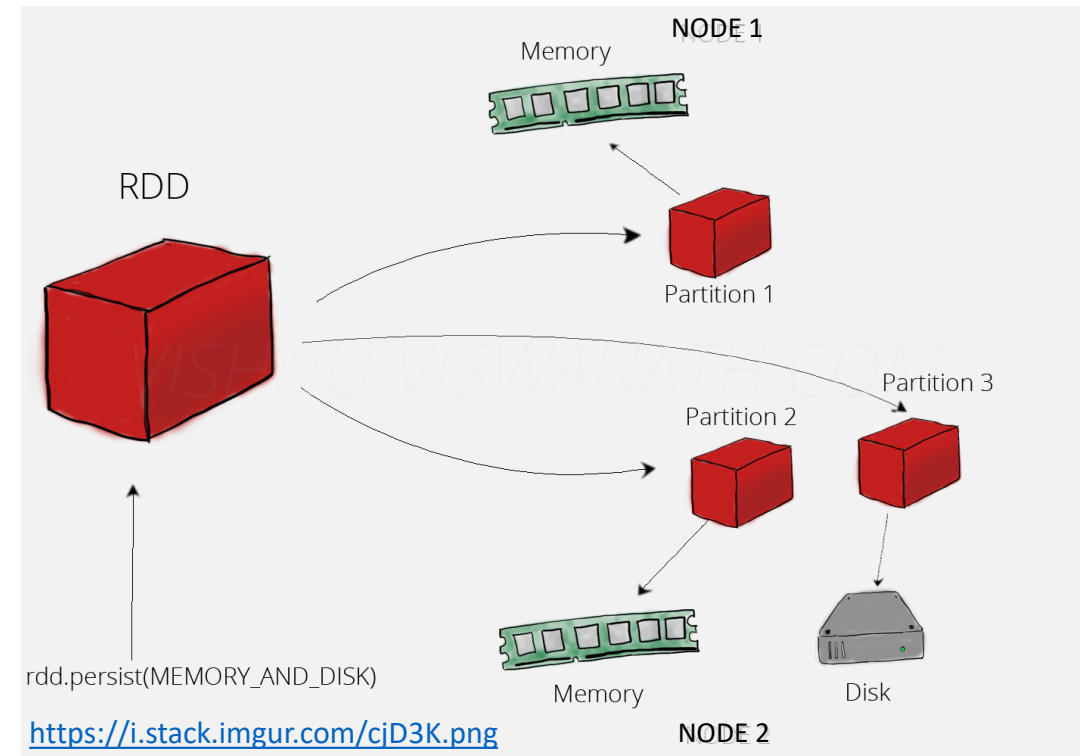
- 1) read data;
- 2) sum within partitions;
- 3) combine sums in driver

Put transform and action together:

errors.filter(_.contains("HDFS")).map(_split('\t')(3)).collect()

RDD Persistence

- Nodes store partitions for **reuse** in other actions on that dataset
- Storage levels for each persisted RDD
 - MEMORY_ONLY (**default**)
 - MEMORY_AND_DISK (**DataFrame default**)
 - Unfit partitions: to be recomputed when needed
- **cache()** = **persist**(StorageLevel.MEMORY_ONLY)



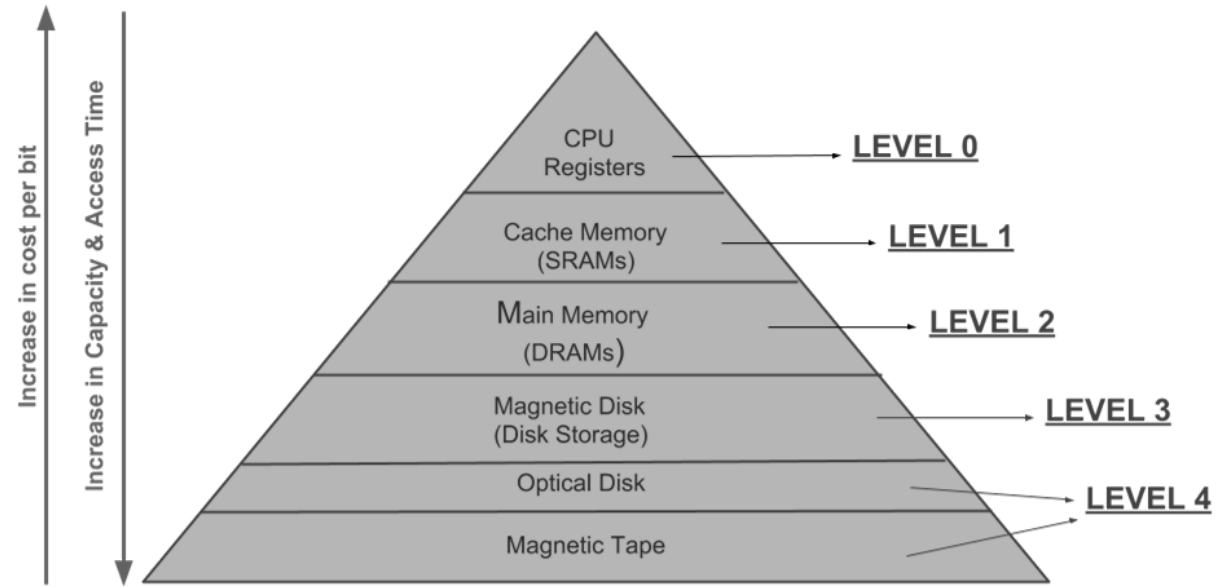
Why Persisting RDD?

```
val lines = sc.textFile("hdfs://...")
```

```
val errors = lines.filter(_.startsWith("Error"))
```

```
errors.persist()
```

```
errors.count()
```



- `errors.count()` again → file reload and re-computation
- `Persist` → cache the data in memory → **reduce the data loading cost** for further actions on **the same data**
- `errors.persist()`: do nothing (a lazy operation, telling “***read this file and then cache the contents***”). An action will trigger computation and data caching.

Spark Key-Value RDDs

- Spark supports [key-value pairs](#)

groupByKey (<i>numPartitions</i>)	When called on a dataset of (K, V) pairs, returns a dataset of (K, Iterable<V>) pairs. Note: If you are grouping in order to perform an aggregation (such as a sum or average) over each key, using <code>reduceByKey</code> or <code>aggregateByKey</code> will yield much better performance. Note: By default, the level of parallelism in the output depends on the number of partitions of the parent RDD. You can pass an optional <code>numPartitions</code> argument to set a different number of tasks.
reduceByKey (<i>func</i> , [<i>numPartitions</i>])	When called on a dataset of (K, V) pairs, returns a dataset of (K, V) pairs where the values for each key are aggregated using the given reduce function <i>func</i> , which must be of type (V,V) => V. Like in <code>groupByKey</code> , the number of reduce tasks is configurable through an optional second argument.
aggregateByKey (<i>zeroValue</i>)(<i>seqOp</i> , <i>combOp</i> , [<i>numPartitions</i>])	When called on a dataset of (K, V) pairs, returns a dataset of (K, U) pairs where the values for each key are aggregated using the given combine functions and a neutral "zero" value. Allows an aggregated value type that is different than the input value type, while avoiding unnecessary allocations. Like in <code>groupByKey</code> , the number of reduce tasks is configurable through an optional second argument.
sortByKey (<i>ascending</i> , [<i>numPartitions</i>])	When called on a dataset of (K, V) pairs where K implements Ordered, returns a dataset of (K, V) pairs sorted by keys in ascending or descending order, as specified in the boolean <i>ascending</i> argument.

Contents

- Resilient Distributed Datasets

- **DataFrames and Datasets**

`pyspark.sql.DataFrame` `pyspark.pandas`

Spark SQL and
DataFrames

Pandas API on
Spark

Structured
Streaming

Machine
Learning
MLlib

- Machine Learning Pipelines

- Execution Parallelization

Spark Core and RDDs

<https://spark.apache.org/docs/latest/api/python/index.html>

Why DataFrame?

- Challenges

- ETL to/from various semi/unstructured data sources
- Advanced analytics (e.g. machine learning) are hard to express in relational systems

- Solutions

- A **DataFrame** API to perform relational operations on both external data sources and Spark's built-in RDDs
- A highly extensible optimizer **Catalyst** to use Scala features to add composable rule, control code generation, and define extensions

DataFrame-based API for MLlib

- In v2.0, the DataFrame-based API became the primary API for MLlib
 - Voted by the community
 - org.apache.spark.ml, pyspark.ml
- The RDD-based API entered the maintenance mode
 - Still maintained with bug fixes, but no new features
 - org.apache.spark.mllib, pyspark.mllib

Announcement: DataFrame-based API is primary API

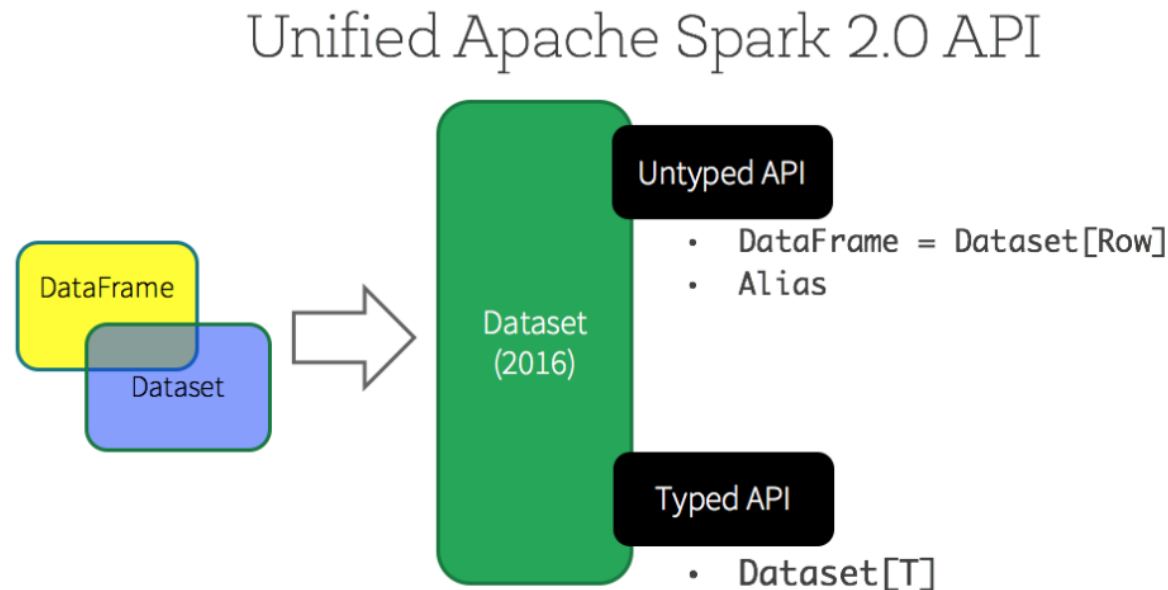
The MLlib RDD-based API is now in maintenance mode.

As of Spark 2.0, the [RDD-based APIs](#) in the `spark.mllib` package have entered maintenance mode. The primary Machine Learning API for Spark is now the [DataFrame-based API](#) in the `spark.ml` package.

What are the implications?

DataFrames and Datasets

- DataFrame: schema, generic untyped (like a table)
- Dataset: static typing, strongly-typed
- DataFrame = Dataset[Row] (Row: generic untyped)
 - Dataset organized into named columns



<https://www.databricks.com/blog/2016/07/14/a-tale-of-three-apache-spark-apis-rdds-dataframes-and-datasets.html>

Benefits of Dataset APIs

- **Static-typing** and runtime type-safety



<https://www.databricks.com/blog/2016/07/14/a-tale-of-three-apache-spark-apis-rdds-dataframes-and-datasets.html>

- High-level abstraction and custom view into structured and semi-structured data, e.g. CSV
- Ease-of-use of APIs with structure
 - Rich **semantics** and domain specific operations
- Performance and optimization
 - SQL Catalyst

Typed and Un-typed APIs

Language	Main Abstraction
Scala	Dataset[T] & DataFrame (alias for Dataset[Row])
Java	Dataset[T]
Python*	DataFrame
R*	DataFrame

* Since Python and R have no compile-time type-safety, we only have untyped APIs, namely DataFrames.

DataFrame

- A distributed collection of rows with the same schema
- Can be constructed from external data sources or RDDs into essentially an RDD of Row objects
- Supports relational operators (e.g. `where`, `groupBy`) as well as Spark operations

dept	age	name
Bio	48	H Smith
CS	54	A Turing
Bio	43	B Jones
Chem	61	M Kennedy

Data grouped into
named columns

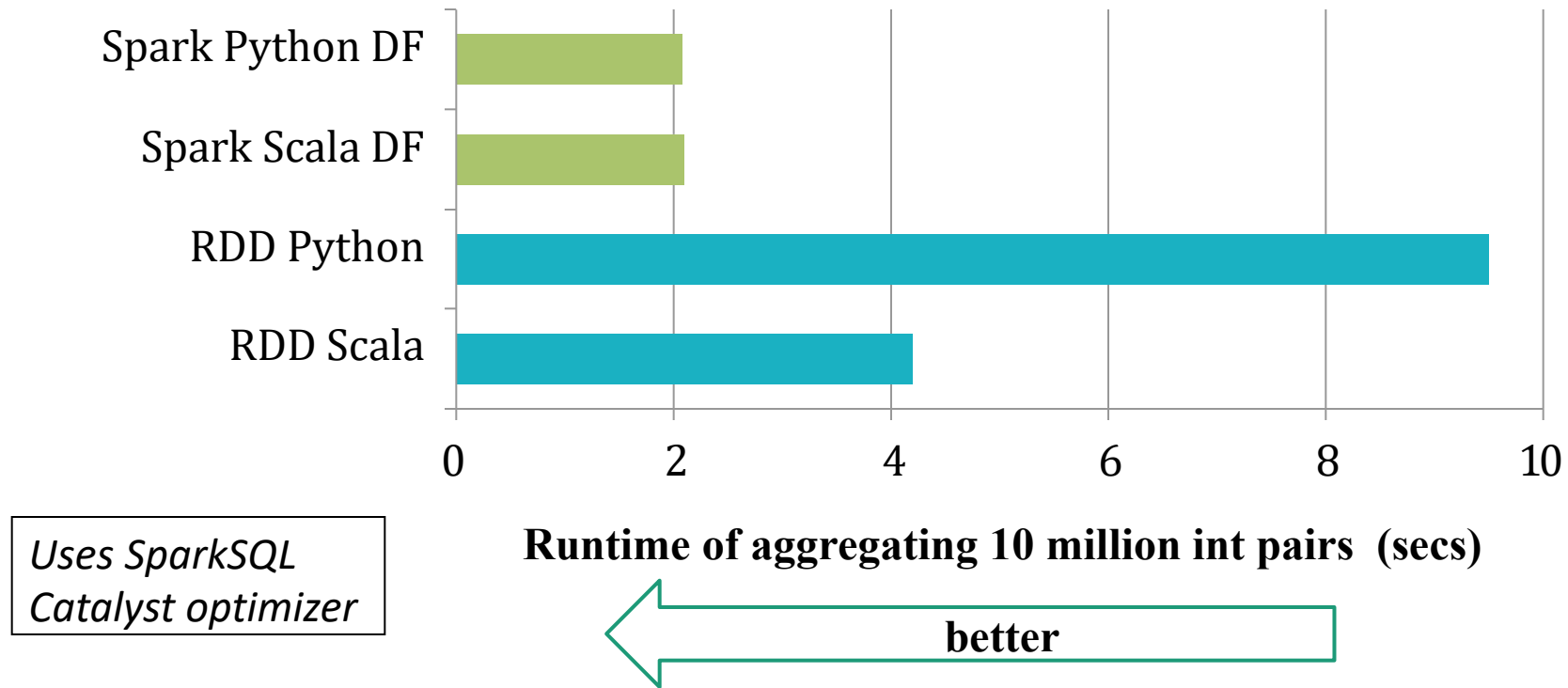
RDD API

```
pdata.map(lambda x: (x.dept, [x.age, 1])) \  
    .reduceByKey(lambda x, y: [x[0] + y[0], x[1] + y[1]]) \  
    .map(lambda x: [x[0], x[1][0] / x[1][1]]) \  
    .collect()
```

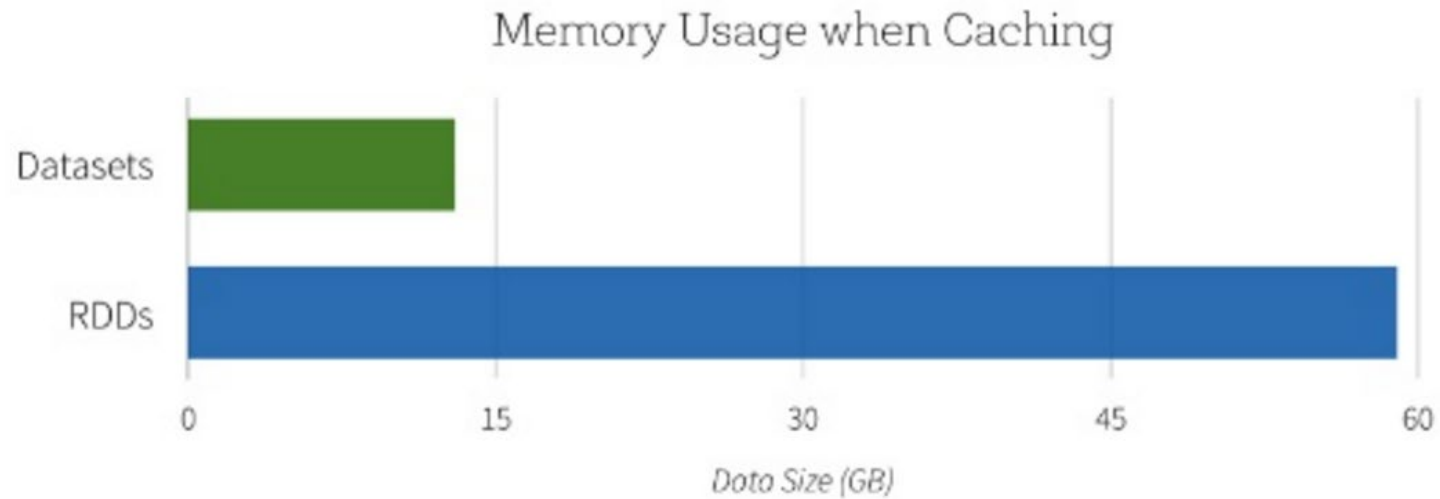
DataFrame API

```
data.groupBy("dept").avg("age")
```


Spark DataFrames are Fast



Space Efficiency



<https://www.databricks.com/blog/2016/07/14/a-tale-of-three-apache-spark-apis-rdds-dataframes-and-datasets.html>

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<https://spark.apache.org/docs/latest/api/python/index.html>

Machine Learning Library (MLlib)

- **ML algorithms**: common ML algorithms for regression, classification, clustering, and collaborative filtering
- **Feature**: feature extraction, transformation, dimensionality reduction, and selection
- **Pipelines**: tools for constructing, evaluating, and tuning ML pipelines
- **Persistence**: save/load algorithms, models, & pipelines
- **Utilities, Statistics, Vector and Matrix, ...**

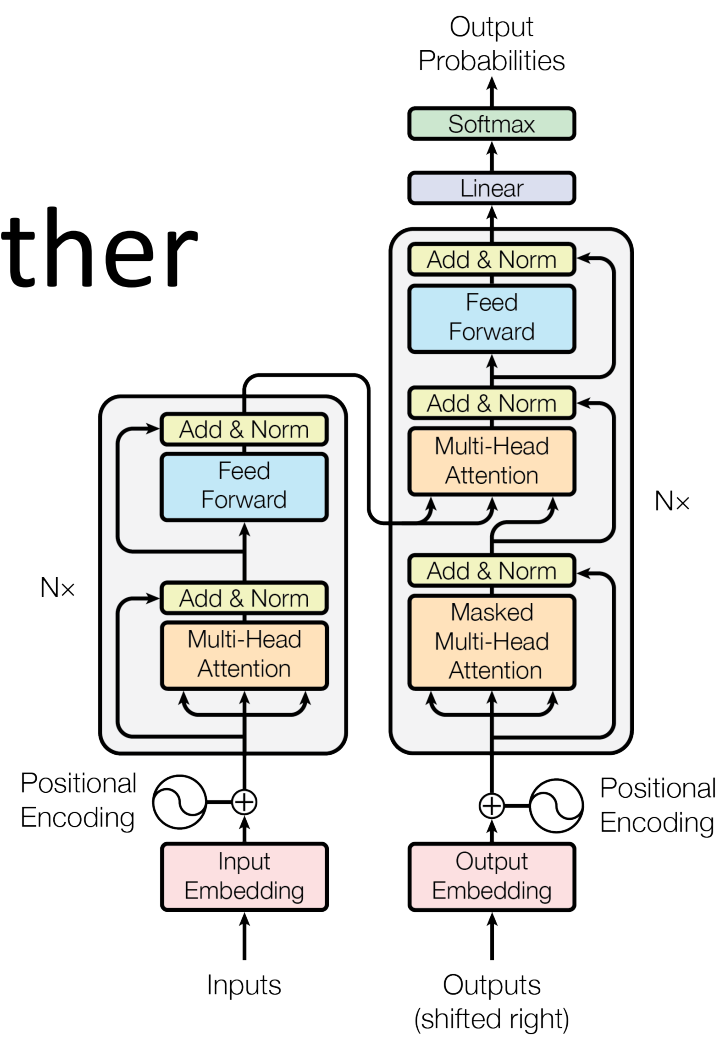
Main Concepts in Pipelines

- **DataFrame**: an ML dataset holding various data types, e.g. columns for text, feature vectors, true labels, & predictions
- **Transformer**: algorithm transforming one DataFrame into another, e.g. features
→ **ML model** → predictions

Transformer in Spark ML Pipelines

Neither

nor



Vaswani, Ashish et al. "Attention is All you Need." *NeurIPS* (2017).

Main Concepts in Pipelines

- **DataFrame**: an ML dataset holding various data types, e.g. columns for text, feature vectors, true labels, & predictions
- **Transformer**: algorithm transforming one DataFrame into another, e.g. features → **ML model** → predictions
- **Estimator**: algorithm fitting on a DataFrame to produce a Transformer, e.g. training data → **ML algorithm** → ML model
- **Pipeline**: chains multiple Transformers and Estimators together to specify an ML workflow
- **Parameter**: all Transformers and Estimators now share a common API for specifying parameters

Example: Text Classification

Goal: Given a text document, predict its topic.

Features

Subject: Re: Lexan Polish?
Suggest McQuires #1 plastic
polish. It will help somewhat
but nothing will remove deep
scratches without making it
worse than it already is.
McQuires will do
something...



Label

1: about science
0: not about science

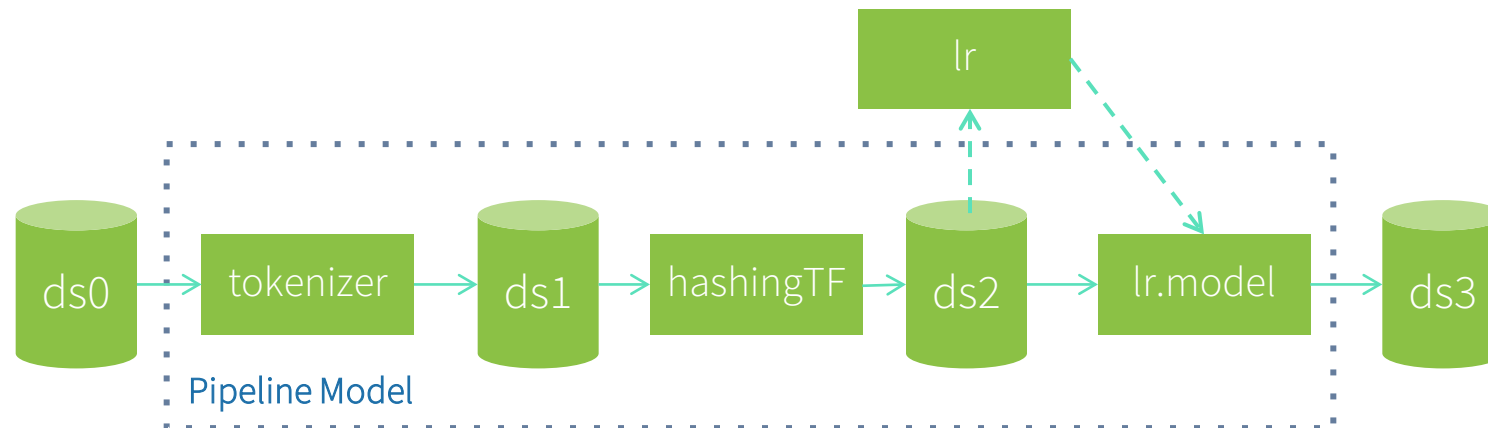
Dataset: "20 Newsgroups"
From UCI KDD Archive

ML Pipelines

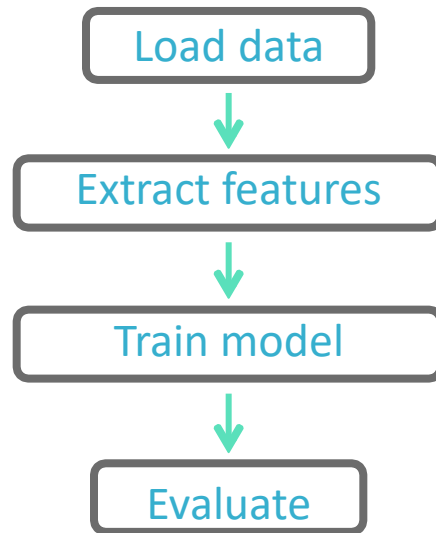
- High-level APIs to create and tune ML pipelines

```
tokenizer = Tokenizer(inputCol="text", outputCol="words")  
hashingTF = HashingTF(inputCol="words", outputCol="features")  
lr = LogisticRegression(maxIter=10, regParam=0.01)  
pipeline = Pipeline(stages=[tokenizer, hashingTF, lr])
```

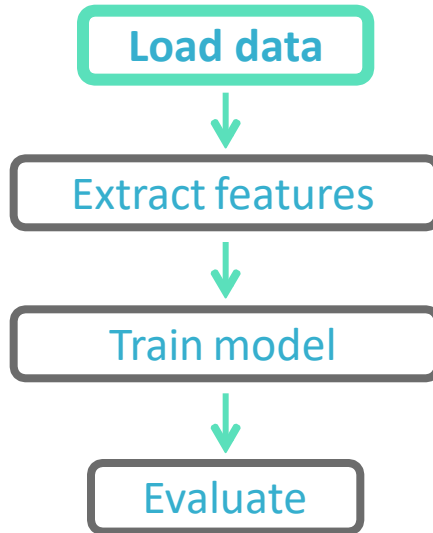
```
df = spark.read.load("/path/to/data")  
model = pipeline.fit(df)
```



ML Workflow



Load Data



Current data schema

label: Int
text: String

Data sources for DataFrames

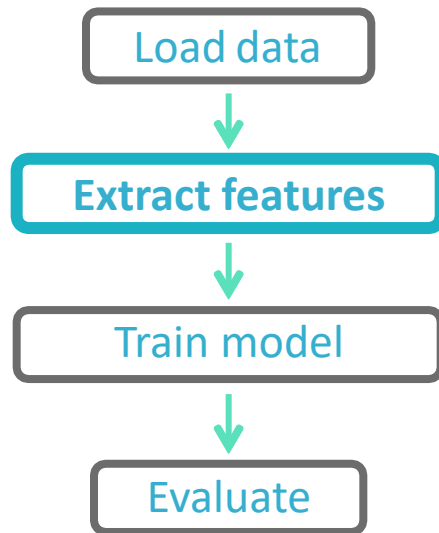
built-in



external



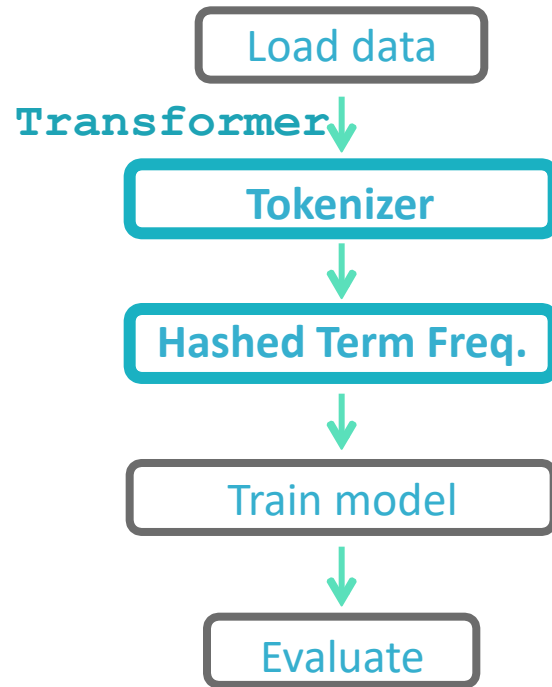
Extract Features



Current data schema

```
label: Int  
text: String
```

Extract Features



Current data schema

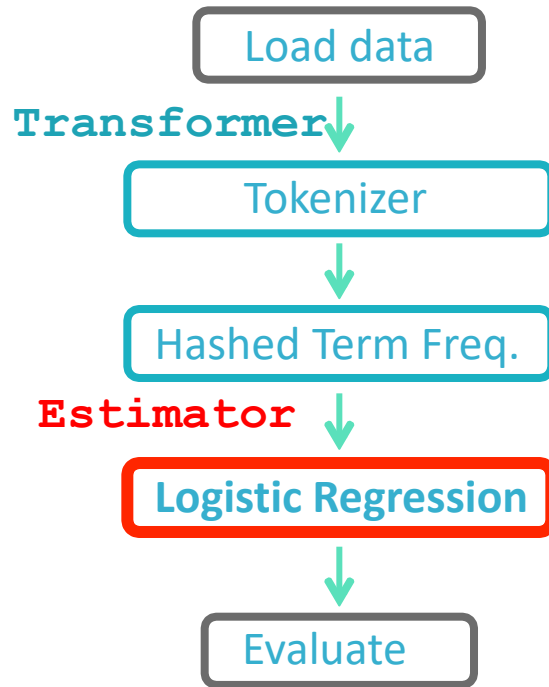
label: Int

text: String

words: Seq[String]

features: Vector

Train the Model



Current data schema

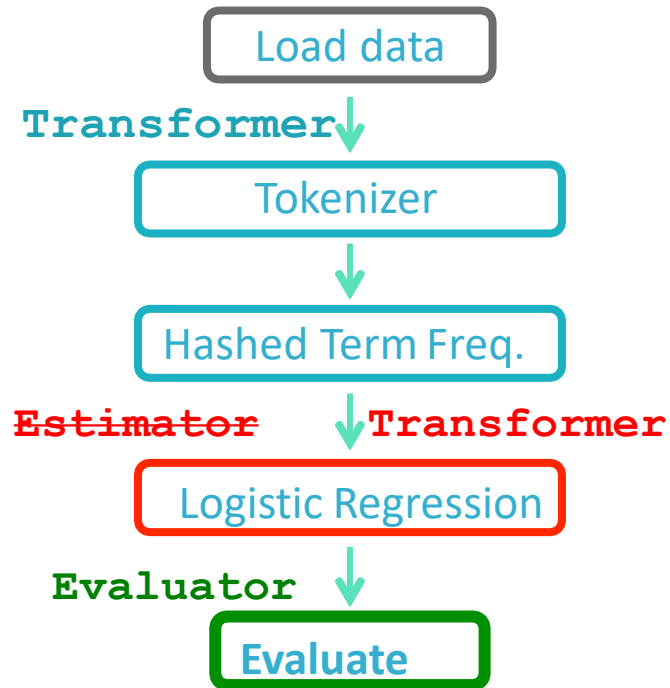
```
label: Int  
text: String
```

```
words: Seq[String]
```

```
features: Vector
```

```
model parameters (not in DF)
```

Evaluate the Model



Current data schema

label: Int
text: String

words: Seq[String]

features: Vector

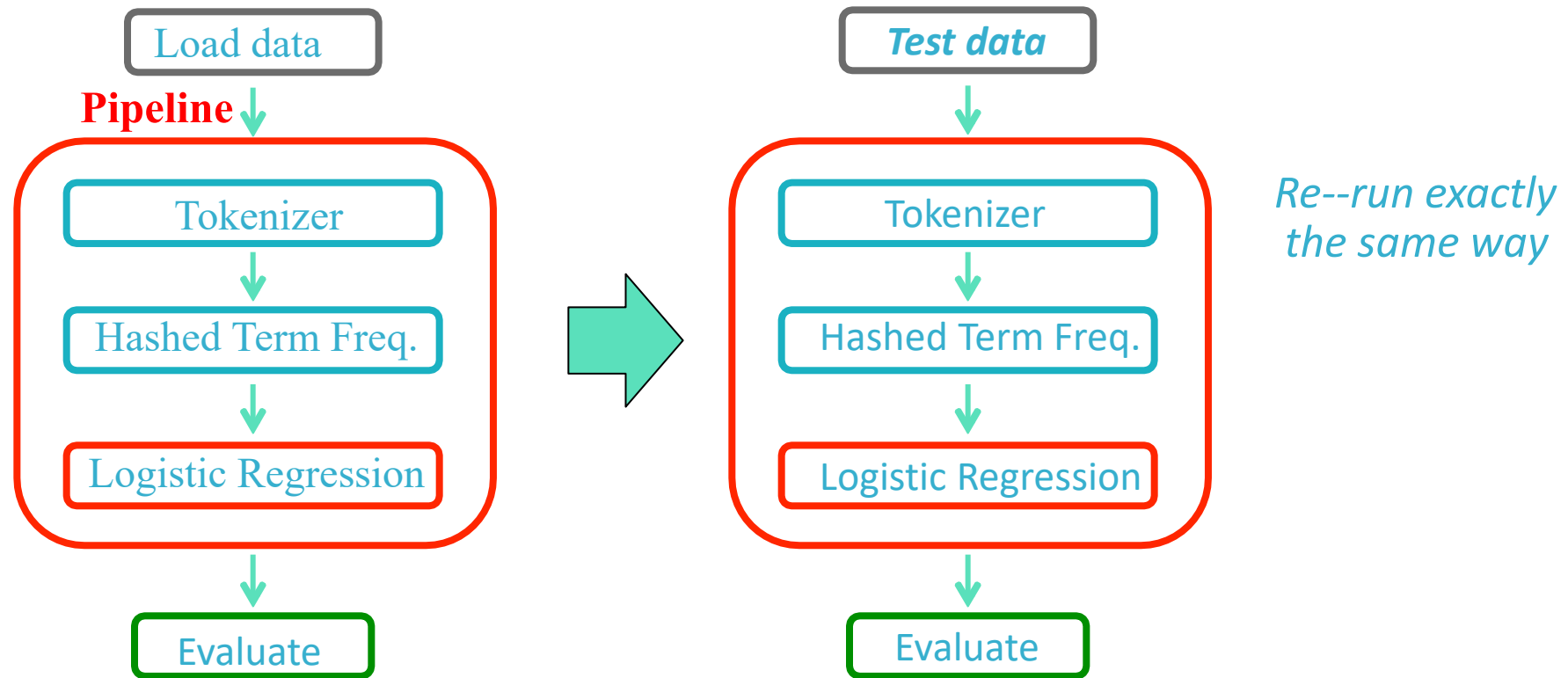
prediction: Int

By default, always append new columns

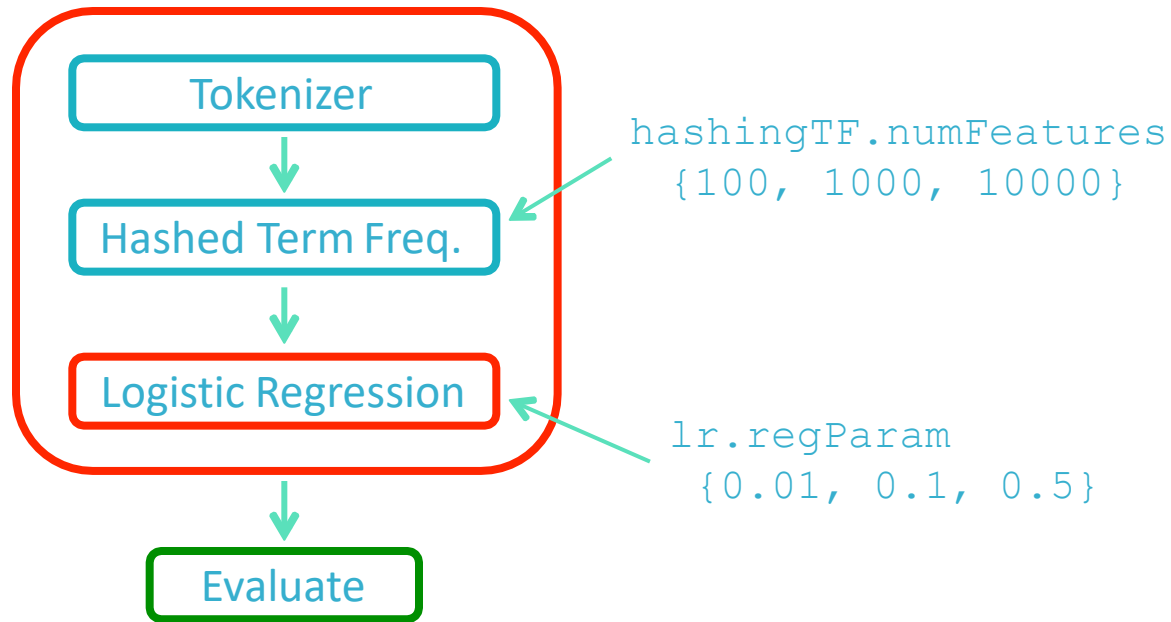
→ Can go back & inspect intermediate results

→ Made efficient by DataFrame optimizations

ML Pipelines



Parameter Tuning



CrossValidator

Given:

- Estimator
- Parameter grid
- Evaluator

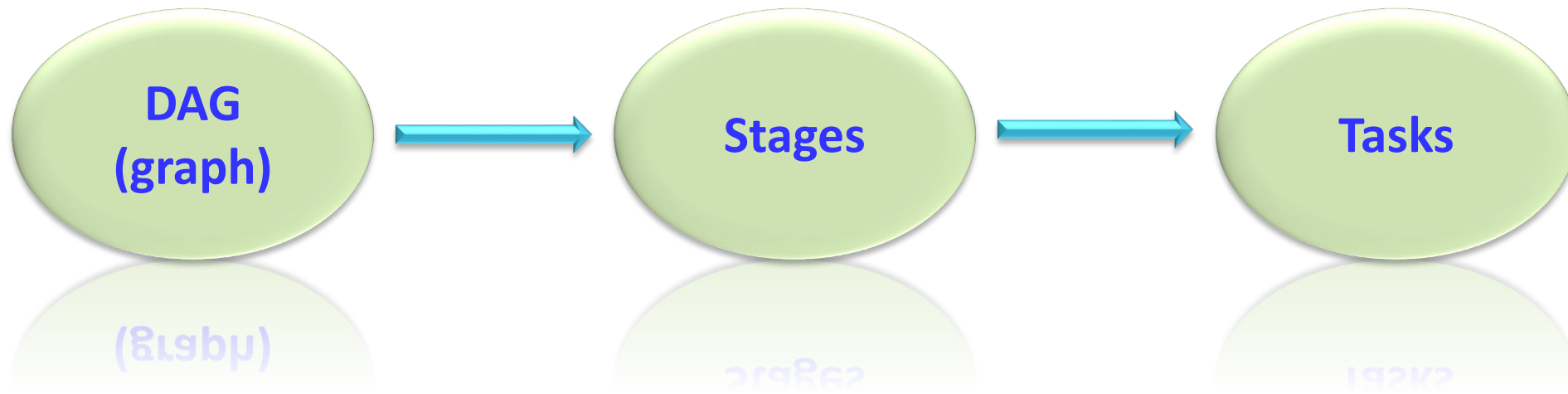
Find best parameters

Contents

- Resilient Distributed Datasets
- DataFrames and Datasets
- Machine Learning Pipelines
- **Execution Parallelization**

How Spark Works

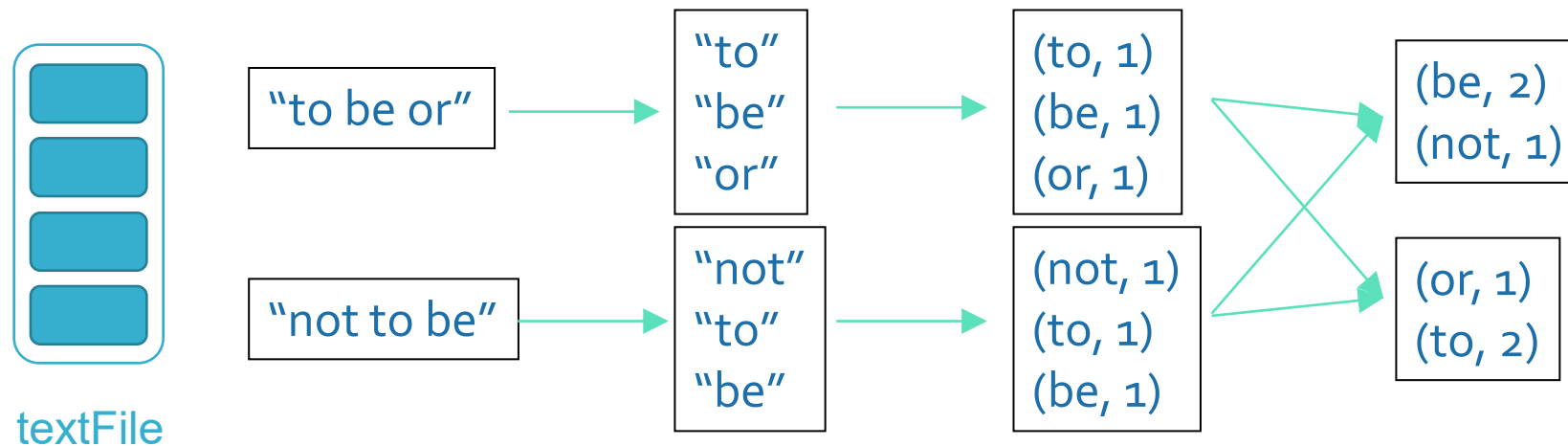
- User applications create RDDs/DFs, transform them, and run actions
- This results in a **Directed Acyclic Graph (DAG)** of operators
- DAG is compiled into **stages**
- Each stage is executed as a series of **tasks**



Word Count in Spark

```
val file = sc.textFile("hdfs://...", 4)
```

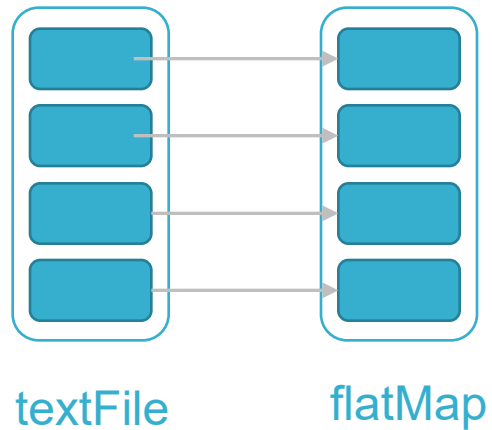
RDD[String]



Word Count in Spark

```
val file = sc.textFile("hdfs://...", 4)  
val words = file.flatMap(line =>  
    line.split("\t"))
```

RDD[String]
RDD[List[String]]



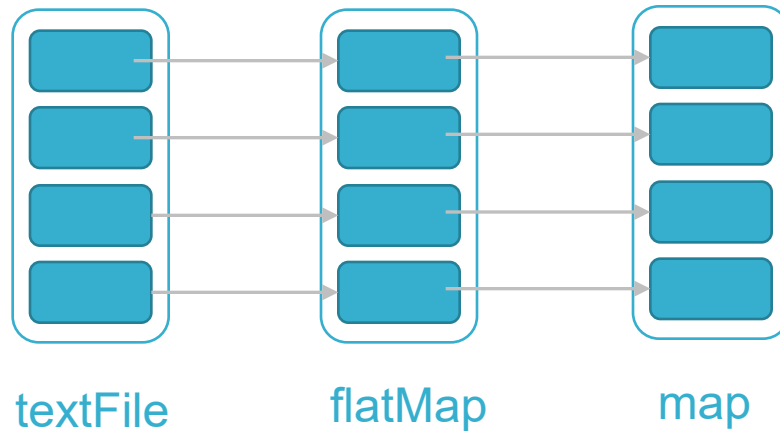
Word Count in Spark

```
val file = sc.textFile("hdfs://...", 4)
val words = file.flatMap(line =>
    line.split("\t"))
val pairs = words.map(t => (t, 1))
```

RDD[String]

RDD[List[String]]

RDD[(String, Int)]

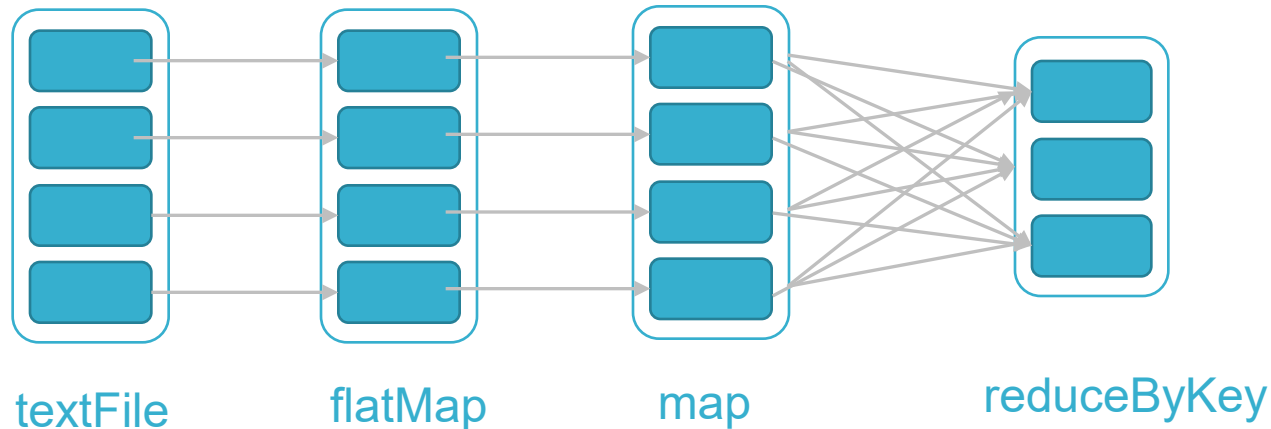


Word Count in Spark

```
val file = sc.textFile("hdfs://...", 4)
val words = file.flatMap(line =>
  line.split("\t"))
val pairs = words.map(t => (t, 1))
val count = pairs.reduceByKey(_+_)
```

RDD[String]
RDD[List[String]]

RDD[(String, Int)]
RDD[(String, Int)]



Word Count in Spark

```
val file = sc.textFile("hdfs://...", 4)
val words = file.flatMap(line =>
  line.split("\t"))
val pairs = words.map(t => (t, 1))
val count = pairs.reduceByKey(_+_)
count.collect()
```

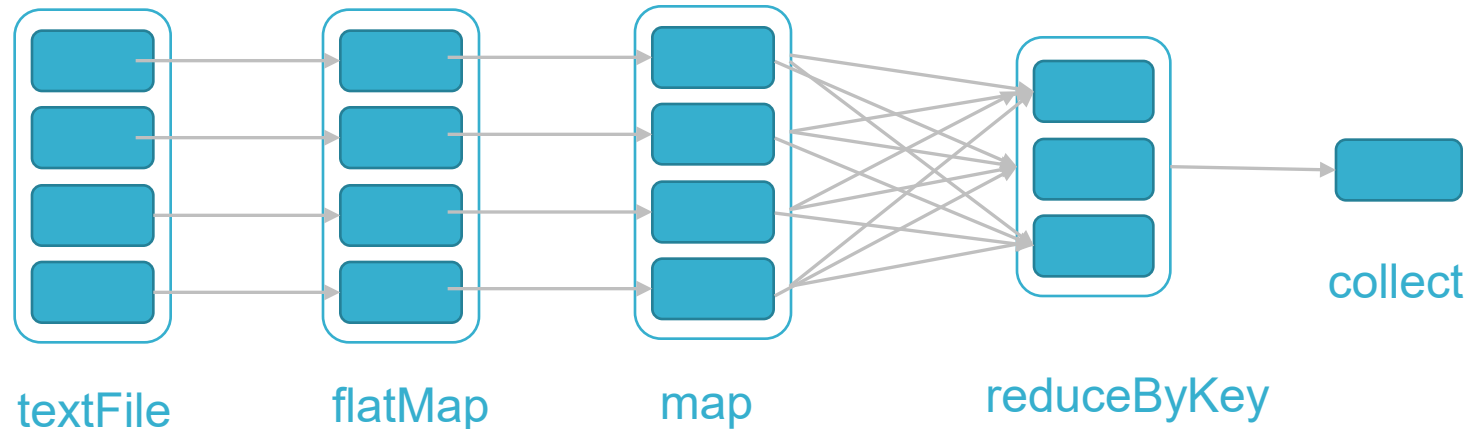
RDD[String]

RDD[List[String]]

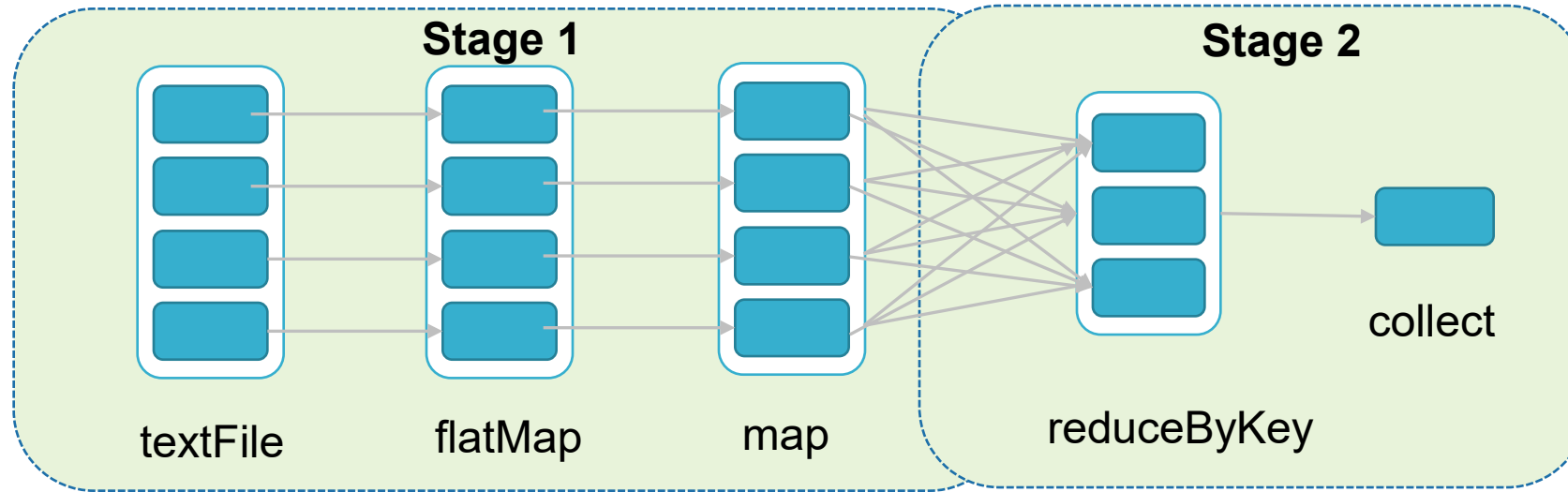
RDD[(String, Int)]

RDD[(String, Int)]

Array[(String, Int)]

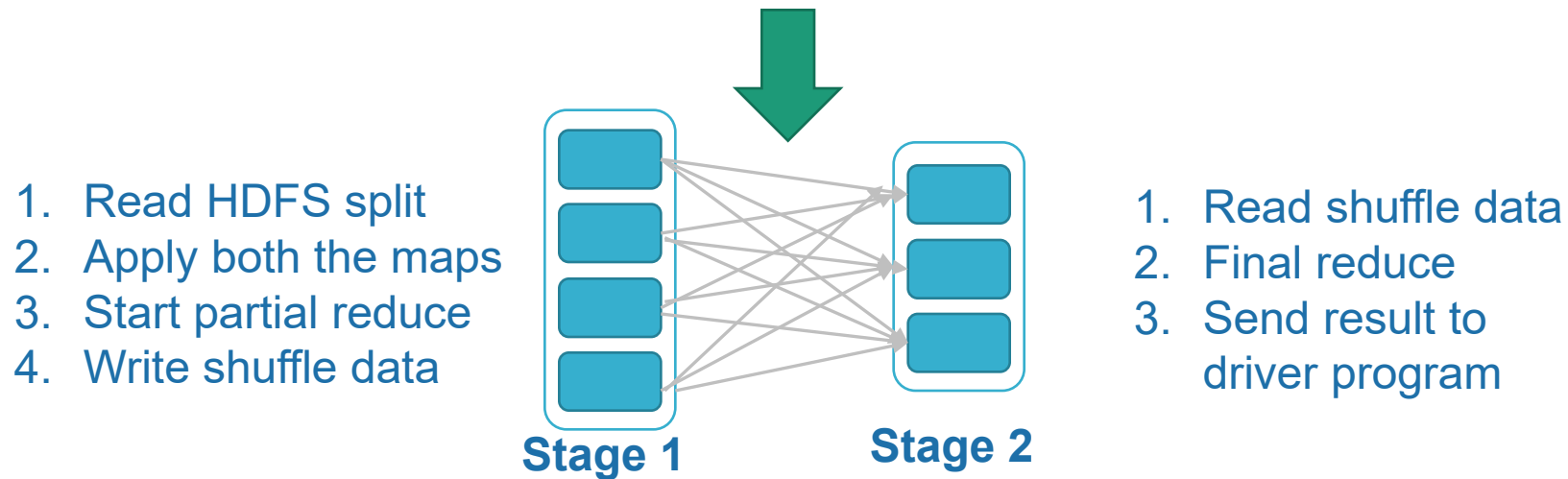
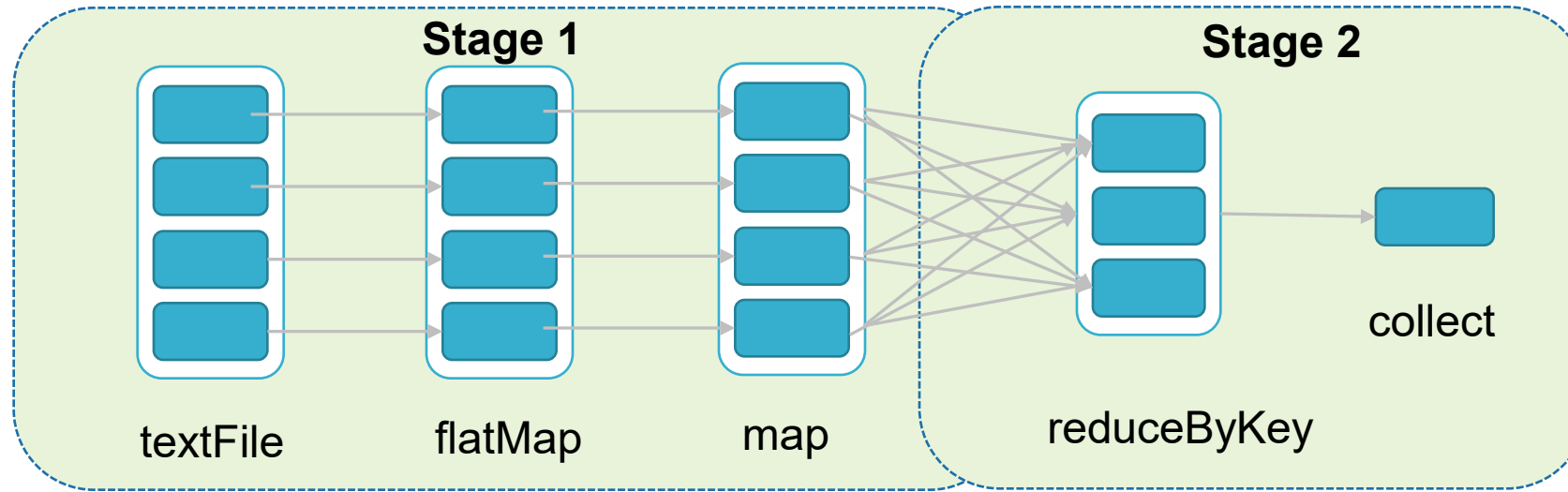


Execution Plan



- The scheduler examines the RDD's lineage graph to build a DAG of stages
- Stages are sequences of RDDs, that don't have a **shuffle** in between

Execution Plan



Execution of Tasks



- Create a **task** for each partition in the new RDD
- Compute the task's closure (those variables and methods that must be visible to the worker)
- Serialize the task's closure
- Schedule and ship tasks (closures) to workers

Setting the Level of Parallelism

- Many transformations take an optional parameter `numPartitions` for number of tasks

<code>distinct([<i>numPartitions</i>])</code>	Return a new dataset that contains the distinct elements of the source dataset.
<code>groupByKey([<i>numPartitions</i>])</code>	<p>When called on a dataset of (K, V) pairs, returns a dataset of (K, Iterable<V>) pairs.</p> <p>Note: If you are grouping in order to perform an aggregation (such as a sum or average) over each key, using <code>reduceByKey</code> or <code>aggregateByKey</code> will yield much better performance.</p> <p>Note: By default, the level of parallelism in the output depends on the number of partitions of the parent RDD. You can pass an optional <code>numPartitions</code> argument to set a different number of tasks.</p>
<code>reduceByKey(func, [<i>numPartitions</i>])</code>	When called on a dataset of (K, V) pairs, returns a dataset of (K, V) pairs where the values for each key are aggregated using the given reduce function <i>func</i> , which must be of type (V,V) => V. Like in <code>groupByKey</code> , the number of reduce tasks is configurable through an optional second argument.
<code>aggregateByKey(zeroValue)(seqOp, combOp, [<i>numPartitions</i>])</code>	When called on a dataset of (K, V) pairs, returns a dataset of (K, U) pairs where the values for each key are aggregated using the given combine functions and a neutral "zero" value. Allows an aggregated value type that is different than the input value type, while avoiding unnecessary allocations. Like in <code>groupByKey</code> , the number of reduce tasks is configurable through an optional second argument.
<code>sortByKey([ascending], [<i>numPartitions</i>])</code>	When called on a dataset of (K, V) pairs where K implements Ordered, returns a dataset of (K, V) pairs sorted by keys in ascending or descending order, as specified in the boolean

Shared Variables (for Cluster)

- Variables are distributed to workers via closures
- When a function is executed on a cluster node, it works on **separate** copies of those variables that are not shared across workers
- **Iterative** or single jobs with large global variables
 - **Problem**: inefficient to send large data with each iteration
 - Solution: Broadcast variables (keep rather than ship)
- Counting events that occur **during** job execution
 - **Problem**: Closures are one way driver → worker
 - Solution: Accumulators (only “added” to, e.g. sums/counters)

Recommended Reading

- [A Tale of Three Apache Spark APIs: RDDs, DataFrames, and Datasets](#)
- [Sections 2.4.2 and 2.4.3 of the MMDS book \(3rd edition\)](#)
- Hyperlinks in slides
- Suggested reading in Lab 2