

## Lectures

### L1: Introduction

#### Four Vs of Data Science

- Volume
- Variety
- Velocity
- Veracity - uncertainty of data

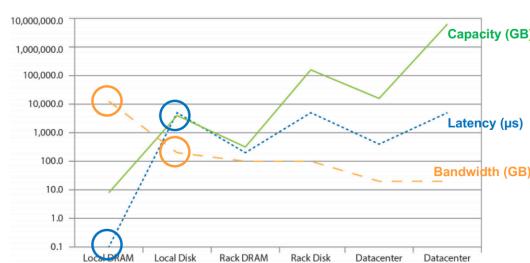
#### Storage Hierarchy

- Volume: Server *le* Rack *le* Cluster
- Speed: Server *ge* Rack *ge* Cluster

#### Bandwidth vs Latency

- **Throughput** Actual rate at which data is transmitted across the network over a period of time
- **Bandwidth** Maximum (capacity) amount of data that can be transmitted per unit time
- **Latency** Time taken for 1 data packet to go from source to destination (or both ways)
- Latency does not matter when transmitting a large amount of data
- Bandwidth does not matter when transmitting a small amount of data

#### Cost of moving data



- Bandwidth drops and latency increases as we move up the data hierarchy
- Disk reads are also much more expensive

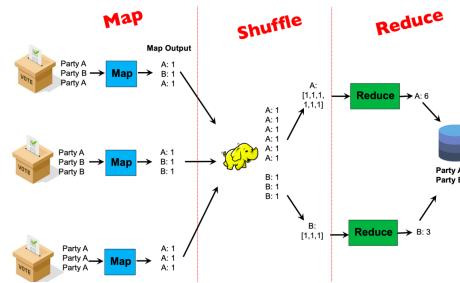
#### Big ideas of data processing

- Horizontal scaling is cheaper than vertical scaling
- Move data processing to the machine with the data since data clusters have limited bandwidth
- Process data sequentially and avoid random access to reduce total seek time
- Seamless scalability → use more machines to reduce time taken to process data

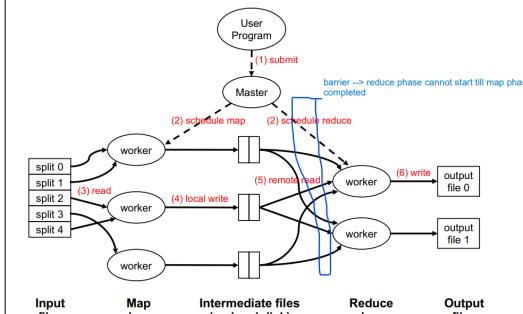
#### Challenges

- Machine failures
- Synchronisation
- Programming difficulty

### L2 Map reduce



- **Map:** extract something of interest from each. Emits a key value pair
- **Shuffle:** Shuffle intermediate results by key value pairs
- **Reduce:** Aggregate intermediate results
- Each of these three processes can occur concurrently across different machines



#### Map Reduce Implementation

1. **Submit:** User submits mapreduce program and configuration (e.g. no. of workers) to Master node
2. **Schedule:** Master schedules resource for map and reduce tasks (master does not handle actual data)
3. **Read:** Input files are separated into splits of 128MB. Each split corresponds to one map task. Each worker executes map tasks 1 at a time
4. **Map phase:** Each worker iterates over each key,value tuple and applies the map function
5. **Local write:** each worker writes the output of map to intermediate files on its local disk. These files are partitioned by key
6. **Remote read:** each reduce worker is responsible for ≥ key. For each key, it reads the data it needs from the corresponding partition of each mapper's local disk
7. **Write:** output of the reduce function is written (usually to a distributed file system such as HDFS)

#### Interface

- $\text{map}(k, v) \rightarrow \text{list}(k', v')$
- reduce

### L3: Map reduce and data mining

#### Secondary Sort

- (Natural Key, Secondary Key)
- Partitioner needs to be customised to partition by the natural key only
- At each reducer, the secondary key (value) will be sorted

#### Projection in Map reduce

- Mapper takes in tuples and emit the appropriate key
- No reducer needed

#### Selection

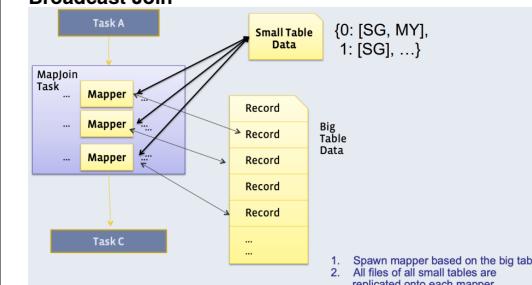
- Mapper takes in a tuple and emit the keys that meet the condition
- No reducer needed

#### Group by aggregation

- E.g. SELECT product id, AVG(price) ... GROUP BY product id
- Framework automatically groups the tuples by the key
- Compute average in reducers

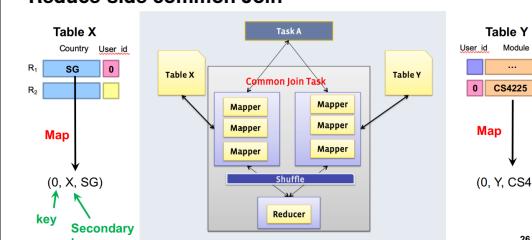
#### Relational Joins

##### Broadcast Join



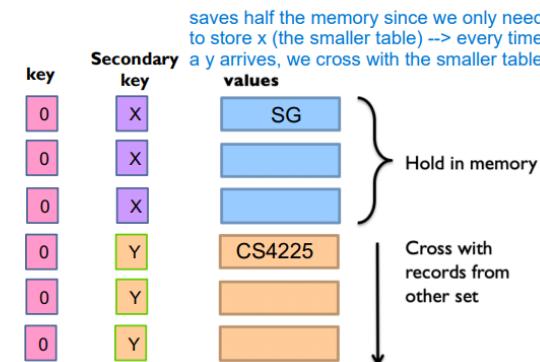
- Requires one of the tables to fit in memory
- All mappers store a copy of the small table
- Iterate over big table to match with small table
- No need reducer

##### Reduce-side common Join

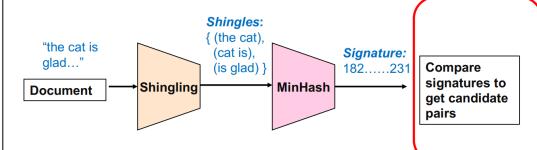


- Don't require a dataset to fit in memory
- Slower than broadcast join
- Different mappers operate on each table, and emit records, with key as the variable to join by
- Secondary sort in reducer ensures that keys from X appear before Y
- Then hold keys from X and use them to join against keys from Y

#### In reduce function for key 0:



#### Finding Similar Docs



#### Shingling

Convert documents into shingles (short phrases)

- **Min-Hashing** Convert phrases into signatures of each document while preserving similarity
- Documents with the same signature are candidate pairs for finding near duplicates
- K-shingle (k-gram) for a doc is a sequence of k tokens that appears in a doc

#### Similarity Metric

## Documents

	D <sub>1</sub>	D <sub>2</sub>	...	
“the cat”	1	1	1	0
“cat is”	1	1	0	1
...	0	1	0	1
	0	0	0	1
	1	0	0	1
	1	1	1	0
	1	0	1	0

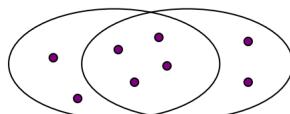
- **Min hash** MinHash gives us a fast approximation to the result using Jaccard similarity instead of doing pairwise comparison
- Min hash converts large sets to short signatures while preserving similarity

### Min Hashing

#### Jaccard similarity:

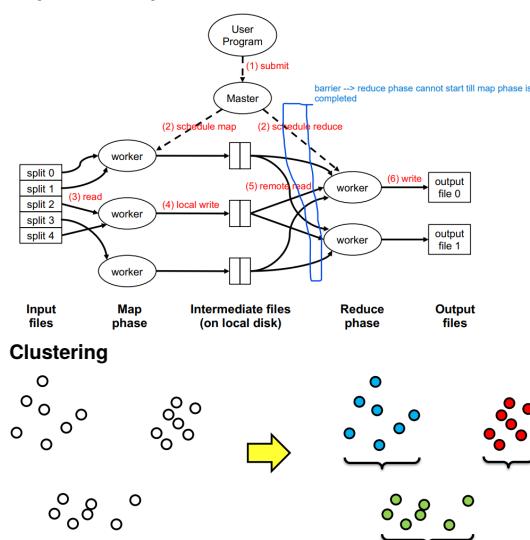
AND OR

$$\text{sim}(D_1, D_2) = |C_1 \cap C_2| / |C_1 \cup C_2|$$

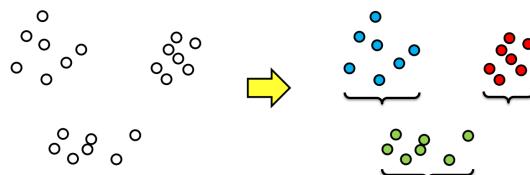


- Hash column c to h(c), such that the table can fit in memory
- sim(c1, c2) is high, then h(c1) == h(c2), if low h(c1) != h(c2)
- Shingles: (the cat), (cat is), (is glad)
- Step 1: h("the cat") = 12, h("cat is") = 74, h("is glad") = 48
- Step 2: Compute the minimum, min(12, 74, 48) = 12
- The probability that two documents have the same min hash is the same as their Jaccard similarity
- Multiple hash functions are used IRL, and the candidate pair is a pair with a sufficient number of matching hash

## MapReduce Implementation



### Clustering



- Separates unlabelled data into groups of similar points
- Clusters have high intra cluster similarity and low inter cluster similarity

### Steps

1. Initialisation: Pick K random points as centres
2. Repeat:
  - Assign each point to nearest cluster
  - Move each cluster to average of its assigned centres
3. stop if no assignment change

### Map Reduce V1

```

1: class Mapper
2: method Configure()
3:   c <- LoadClusters()
4: method Map(id i, point p)
5:   n <- NearestClusterID(clusters c, point p)
6:   p <- ExtendPoint(point p)
7:   Emit(clusterid n, point p)
  
```

```

1: class Reducer
2: method Reduce(clusterid n, points [p1, p2, ...])
3:   s <- InitPointSum()
4:   for all point p 2 points do
5:     s <- s + p
6:   m <- ComputeCentroid(point s)
7:   Emit(clusterid n, centroid m)
  
```

### Map Reduce V2

```

1: class Mapper
2: method Configure()
3:   c <- LoadClusters()
4:   H <- InitAssociativeArray()
  
```

5: method Map(id i, point p)

```

6:   n <- NearestClusterID(clusters c, point p)
7:   p <- ExtendPoint(point p)
# We emit the hashed array instead of emitting by point
8:   H{n} <- H{n} + p

9: method Close()
10: for all clusterid n 2 H do
11:   Emit(clusterid n, point H{n})

1: class Reducer
2: method Reduce(clusterid n, points [p1, p2, ...])
3:   s <- InitPointSum()
4:   for all point p 2 points do
5:     s <- s + p
6:   m <- ComputeCentroid(point s)
7:   Emit(clusterid n, centroid m)

• O(kmd) disk IO, inefficient
  
```

## L4: NoSQL Overview

### NoSQL

- Not Only SQL: can include sql
- Stores data in a format other than relational DB
- SQL refers to relational DBMS, not the querying language - NoSQL can have querying lang too
- Used for large volumes of data and data that does not fit in a structured data (e.g. some has image, some don't)

### Properties

- Horizontal Scalable: easy to partition and distribute across machines
- Replicate and distributed over many servers
- Simple call interface
- Often weaker concurrency model than RDBMS
- Efficient use of distributed indexes and RAM
- Flexible schema

### Major NoSQL DB

- Key-value stores
  - Stores mapping (associations) between keys and values
  - Keys are usually primitives (int,str,raw bytes etc) that can be easily queried
  - Values can be primitive or complex; usually cannot be easily queried (lists, JSON, HTML, BLOB)
  - Eventually consistent
- Operations
  - Get - fetch value with key
  - Put - set value with key
  - Multi-Get, multi-put, range queries (must be comparable, e.g. int, str)

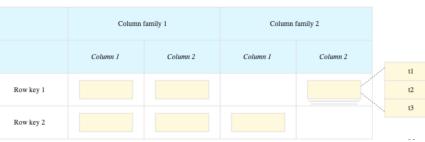
### Suitable for

- Small continuous read and writes
- Storing basic information or no clear schema
- Complex queries are rarely required
- Improves scalability and efficiency of read and writes
- Eventually consistent, so the data might be stale
- E.g. Storing user sessions, caches, user data that is often processed individually

### Implementation

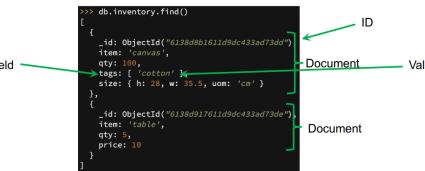
- Non-persistent: Just a big in memory hash table (E.g. redis, memcached) that needs to be regularly backed up to disk
- Persistent: data is stored persistently to disk (E.g. RocksDB, Dynamo, Riak)

### Wide-column databases - stored sparsely



- Rows describe entities
- Related groups of columns are grouped as column families (similar to separate tables, except they share the same row)
- Sparsity: If a column is not used for a row, it doesn't use space (saves space for sparse data)

### Document stores



- no schema (flexible schema)
- A database can have multiple collections
- A collection (tables) can have multiple documents (rows)
- A document is a JSON-like object with field (columns) and values
- Different documents can have different field and can be nested
- Flexible Schema: accommodates data with different characteristics
- **Querying**
  - Unlike key val stores, doc stores allow querying based on the content
  - If the field does not exist on the doc, we just skip it when doing CRUD

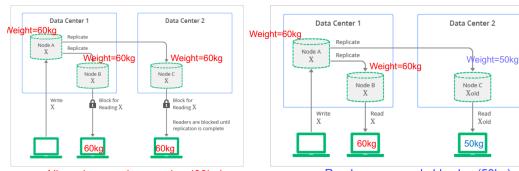
### Graph databases

- Need to store information about the nodes and edges
- Edges: relationship between data (nodes)
- Good at modelling and querying complex relationships between entities
- Good for modelling data as graph problems (traversing relationships, shortest path, social networks etc)

### Vector Databases

- Store vectors (each row is a point in d dimensions)
- Usually dense, numerical, and high-dimensional (data with many features)
- Allow fast similarity search via locality sensitive hashing (LSH), similar to min-hashing
- Scalable, real-time updates, replication
- Good for LLM and vision models as they need to be converted to vectors, and search, recommendation, clustering can be easily added
- Good for content based similarity matching
- E.g. Milvus, Radis, MongoDB, Atlas, Weaviate

### Consistency



- Strong: Any reads on all observers immediately read the same result after update (uses locks, higher latency)
- Eventual: If the system is working and we wait long enough, eventually all reads will produce the same value (correctness affected)

#### BASE

- Basically Available - basic writing and reading operations are available most of the time
- Soft state: without guarantees, we only have some probability of knowing the state at any time
- Eventually consistent
- Eventual consistency offers better availability at the cost of weaker consistency
- NoSQL allows for weaker consistency guarantees, and can be tuned to be stronger (tunable consistency)
- Suitable for statistical queries and social media feed but not suited for financial transactions

#### Duplication / Denormalization

- Motivation: Support join statements → how do we join 2 tables to form 1 new table
- Some optimizations in SQL may not be possible in NoSQL
- Denoormalization:**
  - Storage is cheap! Duplicate data to boost efficiency
  - Tables are designed around potential join queries (pre-create the join tables)
  - Good if the query types are fixed
  - What if a field is updated? → changes need to be propagated to multiple table

#### Pros

+ **Flexible / dynamic schema:** suitable for less well-structured data

+ **Horizontal scalability:** we will discuss this more next week

+ **High performance and availability:** due to their relaxed consistency model and fast reads / writes

#### Cons

- **No declarative query language:** query logic (e.g. joins) may have to be handled on the application side, which can add additional programming

- **Weaker consistency guarantees:** application may receive stale data that may need to be handled on the application side

- Depends on:
  - if denormalization is suitable
  - importance of consistency
  - complexity of queries (joins Vs read/write)

## L5: NoSQL and basics of Distributed system

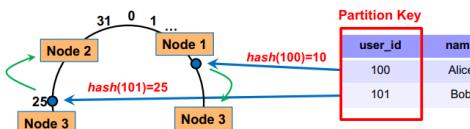
#### Distributed DB architecture

- Shared Everything: Single Node DBMS
- Shared memory: Super Computer
- Shared Disks: Cloud databases
- Shared nothing: NoSQL (mostly)

#### Horizontal Partitioning

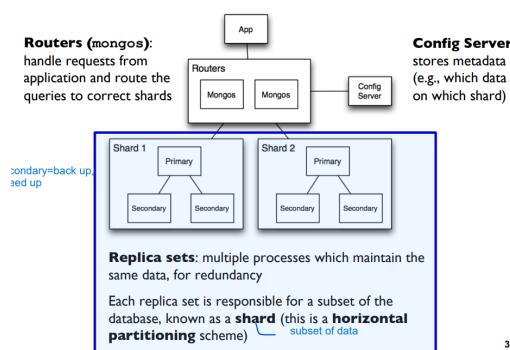
- Partition Key:** variable used to decide which node each tuple will be stored on
- Choose partition key based on a column

- Partition key should have high cardinality but also avoid having a single key being too frequent (node not large enough)
- One way to do this is by using a composite key
- Range Partition:** split partition based on range of values, good for ranged queries but can lead to imbalanced sharding
- Consistent Hashing:**



- Delete: Re-assign tuples clockwise to the next marker
- Replication: replicate and add the tuple in the next few nodes clockwise to the primary node
- Multiple Markers: Have multiple markers per node, such that after deletion we don't create a large imbalance

#### Query Processing in NoSQL



- Horizontal partitioning:** as we get more and more data, we can simply partition it into more and more shards (even if individual tables become very large)
  - Horizontal partitioning improves speed due to parallelization.
- Duplication (i.e. denormalization):** Unlike relational DBs where queries may require looking up multiple tables (joins), using duplication in NoSQL allows queries to go to only 1 collection. sort of pre joining the table via duplication
- Relaxed consistency guarantees:** prioritize availability over consistency – can return slightly stale data

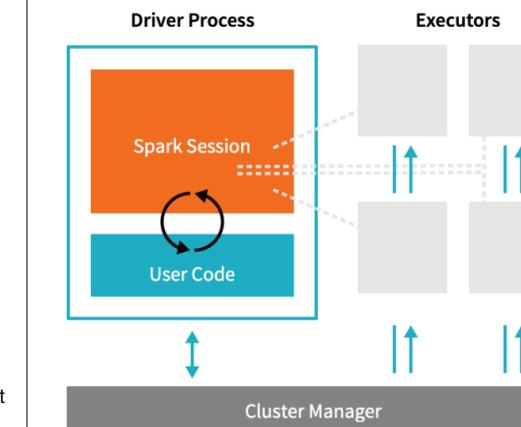
## L6: Sparks Basics I

#### Hadoop Vs Spark

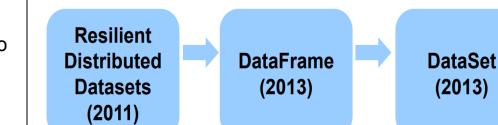
- Spark stores most of intermediate results in memory, making it faster for iterative processing (spillover to disk still happens if memory runs out)
- Hadoop writes intermediate results to local machine / disk. This is not efficient for iterative processing and ML
- Sparks has ease of computability
- Spark combines batch processing, streaming, ML, graph processing

#### Spark Architecture

- Driver process: respond to user input and distributes work to executors
- Executors: executes code and send result back to the driver



#### Evolution of Spark APIs



- \*distributed collection
  - A collection of JVM objects
  - Functional operators (map, filter, etc)
  - Expression-based operations
  - Logical plans and optimizer
- \*not easy to use / efficient, relies on dev to optimise
- \*distributed collection of Row objects
  - A collection of Row objects
  - Expression-based operations
  - Almost the "Best of both worlds": type safe + fast
- \*easier to optimise

#### Lineage Approach

- Using replication is expensive since Spark uses memory

- A faulty node is replaced and recomputed using the DAG from the lost partition (E.g narrow transformations)

#### Resilient Distributed Datasets (RDD)

- Resilient: Fault tolerance through lineage
- Each node executes over 1 partition of data (data parallelism), a RDD is a collection of nodes and the driver
- DDs: collecton of objects distributed over machines
- Immutable

# Create an RDD of names, distributed over 3 partitions

```
dataRDD = sc.parallelize(["Alice", "Bob", "Carol", "Daniel"], 3)
```

#### Transformations

- Transform RDDs into RDDs
- Lazily evaluated, which allows optimisations to be applied over a series of transformations
- E.g.: map, order, groupby, filter, join, select

#### Actions

- Triggers spark to compute result from a series of transformations

```
dataRDD = sc.parallelize(["Alice", "Bob", "Carol", "Daniel"], 3)
```

```
nameLen = dataRDD.map(lambda s: len(s))
```

```
nameLen.collect()
```

- Retrieve all RDD to the driver node
- E.g.: count, collect, show, save

- Spark actions and transformations are calculated in parallel across distributed workers

- RDDs are objects. Completed RDDs are stored in memory and can be flushed out

- Note: transformation work on files in the worker node, not the driver

#### Caching

- Caching:** sometimes we want to reuse RDDs to avoid recomputation

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

```
errors = lines.filter(lambda s: s.startswith("ERROR"))
```

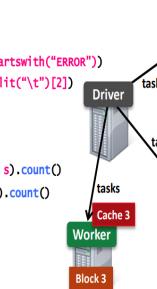
```
messages = errors.map(lambda s: s.split("\t")[2])
```

```
messages.cache()
```

start from here

```
messages.filter(lambda s: "mysql" in s).count()
```

```
messages.filter(lambda s: "php" in s).count()
```



- cache is also a transformation!

- It is lazily done. So it only takes effect after an action

- Cache store an RDD to memory of each worker node

- persist() store RDD to memory or disk or off-heap memory

- RDDs are evicted on a LRU basis so cached RDDs can be evicted

#### Scalability for NoSQL

```

lines = spark.textFile("hdfs://log")
errors = lines.filter(lambda s: s.startswith("INFO"))
info = errors.map(lambda s: s.split("\t") [2])

```

## info.cache()

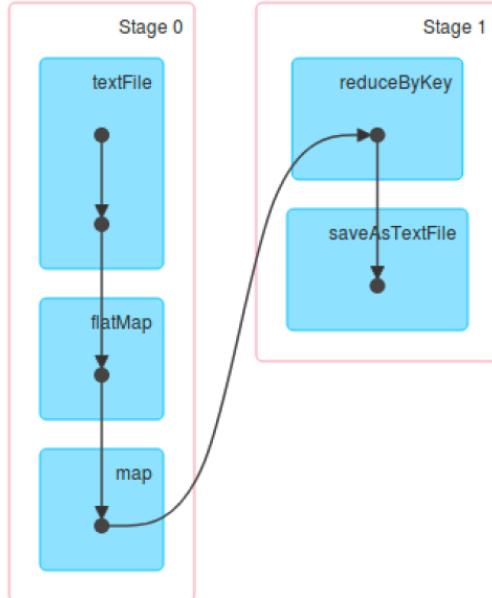
```

info.filter(lambda s: "hadoop" in s).count()
info.filter(lambda s: "spark" in s).count()

```

### DAG

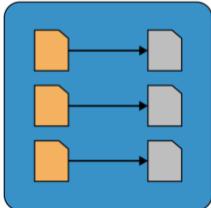
- Represents all RDD objects and order of transformation
- RDDs are functional operations
- Operations here happens in parallel



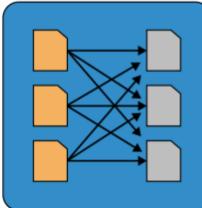
### Narrow and wide dependencies transformation

- Narrow can be linked together
- Wide dependencies are across stage
- Wide: implicit synchronisation effect
- Narrow: each partition of the parent RDD is used by at most 1 partition of child RDD
- Narrow: map, flatmap, filter, contains
- Wide: partition of parent RDD is used by multiple partitions of the child RDD (other worker nodes)
- Wide: reduceByKey, groupBy, orderBy

### Narrow Dependencies



### Wide Dependencies



- Consecutive narrows are grouped as "stages" in DAG

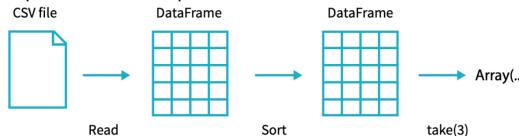
- Within stages: spark computes consecutive transformations on the same machine (pipelined, parallelized)
- Across stage: data needs to be shuffled and intermediary results needs to be written to disk
- Minimize shuffling (across stage)

### Lineage and fault tolerance

- Does not use replication (unlike hadoop) since memory is limited
- Lineage: if a worker is down, we replace it, and use DAG to recompute the data in the lost partition. Lost partition will be recomputed from the RDDs
- The DAG of each RDD has to be stored
- When flushed, the node can start where it stopped within the wide stage later on
- If the job is passed to a new node, the RDD job starts from the start of the stage

### Dataframe

- column based (applied for each attribute)
- Dataframe represents a table of data, similar to tables in sql
- This is a higher level interface that is easier to use
- Implemented with RDDs
- Expression based operation



- Spark can use sql queries for dataframes which is similar to:

```

from pyspark.sql.functions import desc
flightData2015 \
    .groupBy("DEST_COUNTRY_NAME") \
    .sum("count") \
    .withColumnRenamed("sum(count)", "destination_total") \
    .sort(desc("destination_total")) \
    .limit(5) \
    .collect()

```

### Datasets

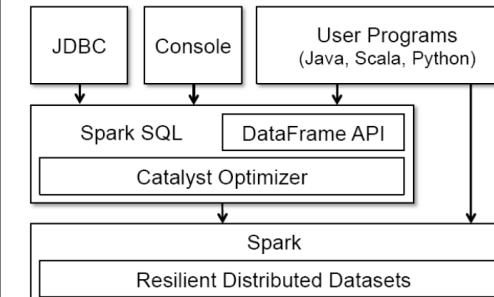
- Type safe version of data frame
  - Datasets are not available in python and R since they are dynamically typed
  - Each row is an object of a user defined class
- ```

case class Flight(DEST_COUNTRY_NAME: String, ORIGIN_COUNTRY_NAME: String, count: BigInt)
val flightsDF = spark.read.parquet("/mnt/defg/flight-data/parquet/2010-summary.parquet")
val flights = flightsDF.as[Flight]
flights.collect()

```

## L7: Spark Basics II

### Spark Pros



- Speed
- Ease of use (can write sql directly)
- Modularity
- Extensibility
- Unified stack for distributed execution
- Keeps track of schema and supports optimised sql operations

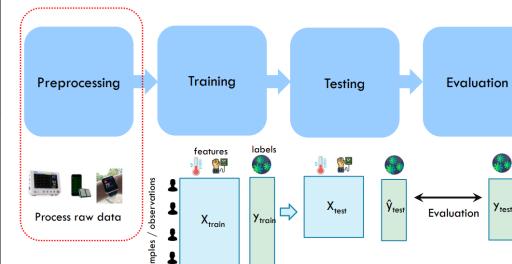
### RDD Vs. Dataframe

- RDD**
  - Instruct Spark how to compute the query
  - The intention is completely opaque to Spark
  - Spark also does not understand the structure of the data in RDDs (which is arbitrary Python objects) or the semantics of user functions (which contain arbitrary code)
- DataFrame**
  - Tell Spark what to do, instead of How to do
  - The code is far more expressive as well as simpler
    - Using a domain specific language (DSL) similar to python pandas
    - Use high-level DSL operators to compose the query
  - Spark can inspect or parse this query and understand our intention, it can then optimize or arrange the operations for efficient execution

### Catalyst Optimiser

- Analysis
- Logical Optimisation
- Physical Planning
- Code Generation

### ML in Spark



- Missing data:** Fill in missing value(imputation) with mean, or fitting regression model, or by using dummy variables
- imputer = Imputer(inputCols=["a", "b"], outputCols=["out a", "out b"])
- model = imputer.fit(df)
- One Categorical Encoding:** Convert categorical values to binary (is Group1, is not Group1), good if there is no ordinal relationship between the categories

- True positive**

| Ground Truth Label (y) |    |    |
|------------------------|----|----|
| Predicted Label (y)    | 0  | 1  |
| 0                      | TN | FN |
| 1                      | FP | TP |

True Positive: test correctly output positive  
 True Negative: test correctly output negative  
 False Positive: test wrongly outputs positive  
 False Negative: test wrongly outputs negative

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- $TN + TP = \text{Accuracy}$
- $\frac{TP}{TP+FN}$  is sensitivity (actual positives detected)
- $\frac{TN}{TN+FP}$  is specificity (actual negatives detected)

### Pipelines

- Better code reuse

## L8: Streams

### Motivation

- Data arrives overtime (online) via message queue, file stream etc
- System cannot store the entire stream, so we have to process the data as they arrive
- E.g. search, online activity data, sensor data, financial data
- Cannot wait till all the data is received to decide

### Fault Tolerance

- Need to be able to store and access intermediate data
- Non-stateful stream processing is not accurate

### Spark stream processing - structured streaming

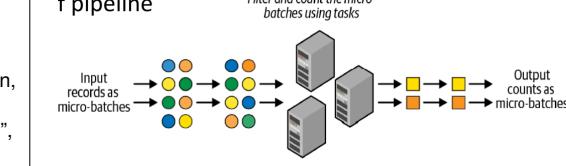
- Micro Batch model: Divides data from input stream into micro batches
- Each batch is processed in a distributed manner
- Small, deterministic task generates the output to batches
- Advantages**

- Quick and efficiently recover from failures (process the failed batch again, rollover)
- Deterministic nature: end-to-end exactly once processing is guaranteed

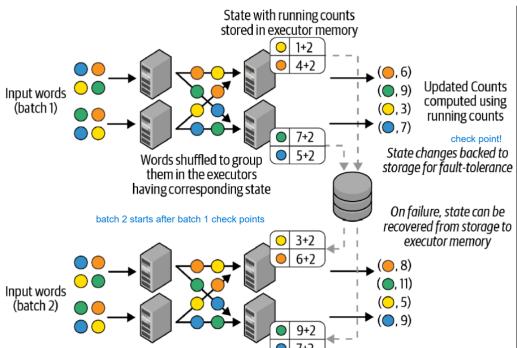
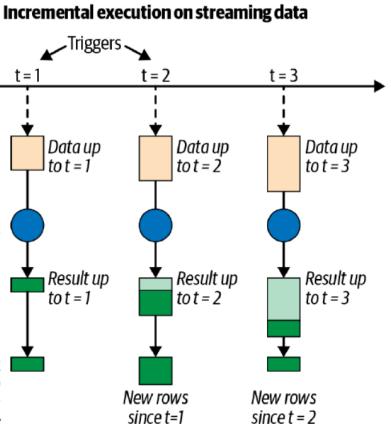
### Disadvantages: High throughput, high latency

- Latency of a few seconds - need to wait for all records in the microbatch to be completed
- Application may experience higher delay in other parts of the pipeline
- The latency might be too high for some

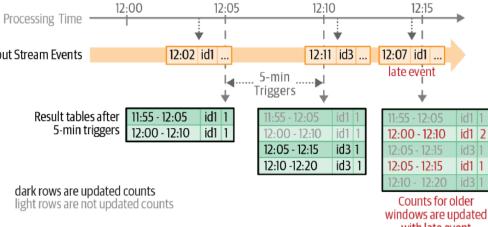
### f pipeline



- Treat the table as unbounded, with new rows streaming in
- Data flows in incrementally, new "rows" are processed and the result is appended to the output table as new rows as



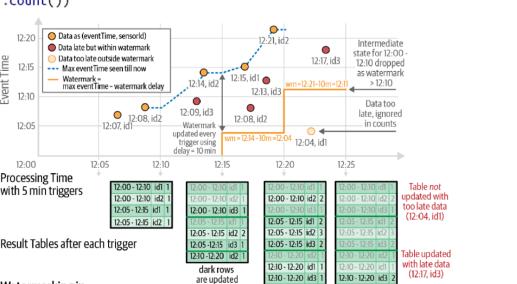
Updated counts in the result table after each five-minute trigger



- Consecutive windows share some data with adjacent windows
- This makes data more continuous and smooth
- Increases data utilization
- Reduces edge effect, where the values at the edge of a event window weights less than the events in the centre
- Prevent loss of information, particularly the data at the edge
- A data that arrives will update =1 window

### Watermark

```
(sensorReadings
    .withWatermark("eventTime", "10 minutes")
    .groupByKey("sensorID", window("eventTime", "10 minutes", "5 minutes"))
    .count())
```

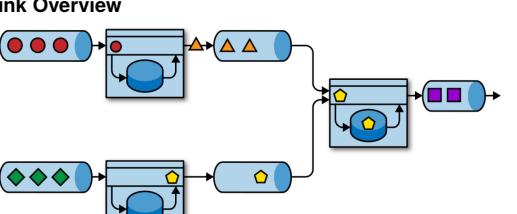


- Water mark: we only track records that are within highest current time - water mark duration: highest current time

### Performance Tuning

- Cluster resources appropriately to avoid running 24/7
- Set partitions for shuffling to be lower than batch queries for streaming data, so that the data in each node is large enough for the batch queries
- Setting source rate limits for stability – prevent incoming stream from breaking spark
- Multiple batch,streaming queries, ML can have at once

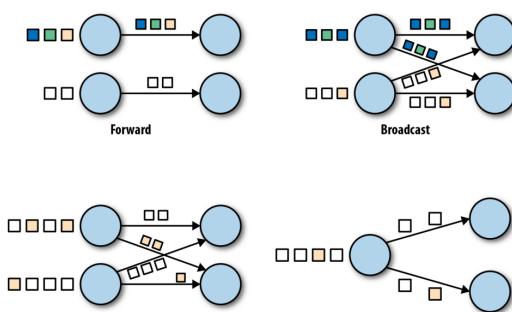
### Flink Overview



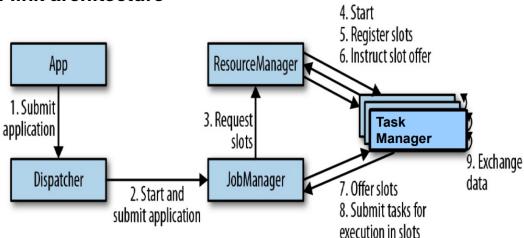
- distributed system for stateful parallel data stream
- Treats stream as a stream
- Achieves microsecond latency

- Event driven, message queue and event logs
- Also has logical plan and physical plan, similar to spark

### Dataflow model

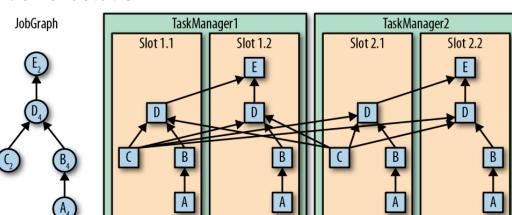


### Flink architecture



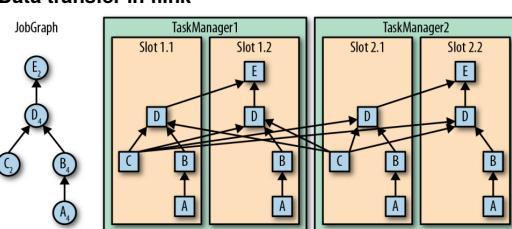
- Resource manager is responsible for scheduling tasks to resources

### Task execution



- Task manager manages slots that processes tasks
- Task manager can execute tasks from different operators and different applications
- C → B, some network shuffling is done

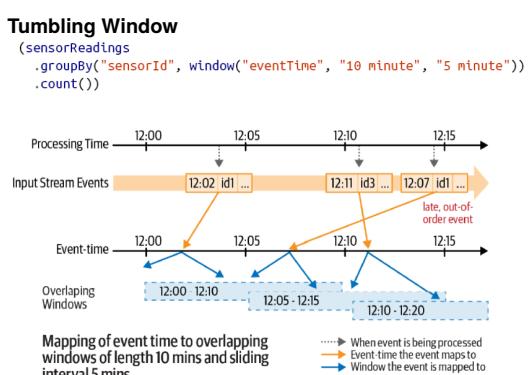
### Data transfer in flink



- Task of an app is continuously exchanging data
- Task manager takes care of sending and receiving data
- Network component of task manager buffers the records before sending
- Send and receive has their own buffer to reduce network traffic, so send and receive are done async (unlike micro

### Data Transformation

- Stateless transformation**
  - Process each row without info from prev rows
  - Projection: select(), explode(), map(), flatmap()
  - Selection: filter(), where()
- Stateful transformation**
  - E.g. df.groupBy().count()
  - partial count is stored somewhere and passed to the next batch
  - It is important to have exact-once even with potential failure and recovery so that the final count is accurate



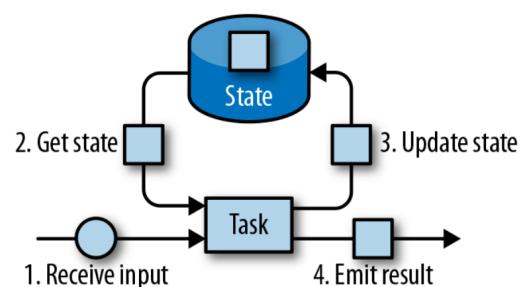
- We tag an id to the event based on the event time
- The id refers to the corresponding tumbling window
- Overlapping Window**

batch)

## Event time processing (Flink)

- Every record has an accompanying time stamp
- Watermark (flink)**
  - more like a trigger mark (spark triggers after every micro batch, so latency is the size of the micro batch) – watermark in flink determines how frequently calculations are triggered!
  - Watermark is represented as special records holding a timestamp
  - Water mark flows in a stream of regular records
  - Heuristic watermark: Results trigger after watermark, late records processed again later
  - Perfect watermark: Late records included, trigger happens after
- ```
PCollection<KV<Team, Integer>> totals = input
    .apply(Window.into(FixedWindows.of(TWO_MINUTES))
        .triggering(AfterWatermark()
            .withEarlyFirings(AlignedElaev(ONE_MINUTE))
            .withLateFirings(OneCount(1)))
        .apply(Sum.integersPerKey()));
```
- withLateFiring** determines when to drop late records

## State Management in Flink



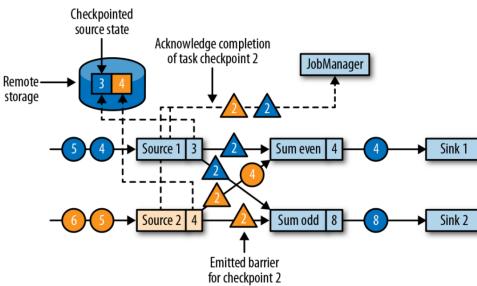
## Operator State

- Scoped to an operator task, cannot be accessed by other operators
- All records processed by the same parallel task have access to the same state

## Consistent Checkpointing

- Similar to micro batch checkpoint
- Pause the ingestion of all input streams
- Wait for in-flight data to be completely processed (all tasks processed their inputs)
- Like a barrier? Need to finish the whole "microbatch"
- Copy and store state to a persistent storage
- Need to reset from latest checkpoint – cannot achieve millisecond delay!

## Chandy-lamport algorithm



## Distributed checkpoints

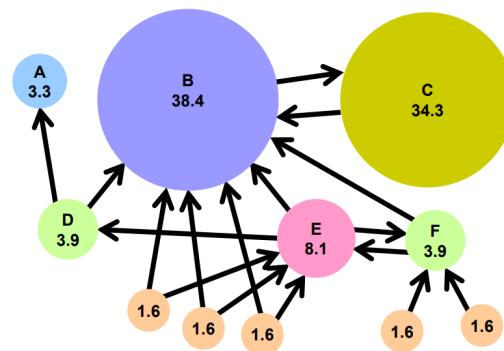
- Decouples checkpointing from processing, does not pause the entire app, only some tasks pause
- Sets up a checkpoint barrier, all tasks to perform this barrier in a distributed way
- After receiving the checkpoint message, the source will save their state and broadcast checkpoint barrier to the receiving nodes
- Tasks will buffer the records for barrier alignment (only process once they receive the barrier msg from all sources)
- Only the tasks receiving the barrier will buffer
- After receiving all checkpoint barriers, the task will save their state
- Then the barrier is emitted to the next level (sink nodes)
- The jobManager is notified once all the tasks have completed the checkpoint

## Spark vs Flink

- Spark**
  - Microbatch streaming processing (latency of a few seconds)
  - Checkpoints are done for each microbatch in a synchronous manner ("stop the world")
  - Watermark: a configuration to determine when to drop the late events
- Flink**
  - Real-time streaming processing (latency of milliseconds)
  - Checkpoints are done distributedly in an asynchronous manner (more efficient → lower latency)
  - Watermark: a special record to determine when to trigger the even-time related results
  - Flink uses late handling functions (related to watermark) to determine when to drop the late events

## L9: Graphs and Page Ranks

### Page Rank Algorithm



- Web as a directed graph, with each node as a webpage and each edge as a hyperlink

- Quantify the importance of web pages on the internet
- Use the 'votes' from other webpages to determine the importance of a webpage
- The weight of each vote is determined by the importance of the webpage casting the vote

### Voting Formulation

- A page is important if it is pointed to by other important pages

- Define a "rank" or importance  $r_j$  for page  $j$

$$r_j = \sum_{i \rightarrow j} \frac{r_i}{d_i}$$

$d_i$  = number of out-links (or "out-degree") of node  $i$

Importance of  $j$

Sum of importances of pages linking to  $j$ , each divided by number of out-links

"Flow" equations:  
 $r_y = r_x/2 + r_a/2$   
 $r_z = r_x/2 + r_m$   
 $r_m = r_x/2$

- No unique solution
- All solutions are rescalings of each other
- Additional constraint:  $r_y + r_a + r_m = 1$
- Even with the additional constraint, calculating page rank for a large graph is still difficult

### Matrix Formulation

- Let page  $i$  has  $d_i$  out-links
- If  $i \rightarrow j$ , then  $M_{ji} = \frac{1}{d_i}$  else  $M_{ji} = 0$
- $M$  is a **column stochastic matrix**
  - Columns sum to 1

### Rank vector $r$ : vector with an entry per page

- $r_i$  is the importance score of page  $i$
- $\sum_i r_i = 1$

### The flow equations can be written

$$r = M \cdot r$$

This is equivalent to our earlier formulation:

$$\text{For all nodes } j: r_j = \sum_{i \rightarrow j} \frac{r_i}{d_i}$$

- Suppose  $M$  is  $i \times j$ ,  $\text{edge}_{j,i}$  is the column  $j$  voting for web page  $i$  with the weight of the vote being  $M_{i,j}$

### Power Iteration Method

#### Power iteration: a simple iterative scheme

- Suppose there are  $N$  web pages
- Initialize:  $r^{(0)} = [1/N, \dots, 1/N]^T$
- Iterate:  $r^{(t+1)} = M \cdot r^{(t)}$  Equivalent!
- Stop when  $\|r^{(t+1)} - r^{(t)}\|_1 < \epsilon$

$$d_i \dots \text{out-degree of node } i$$

$|x_i| = \sum_{1 \leq i \leq N} |x_i|$  is the L1 norm  
Can use any other vector norm, e.g., Euclidean

- Stop condition: stop when the 2 iterations differ by a small amount, convergence
- For some convergence or weird topology, it may not converge

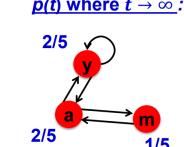
### Random Walk Formulation

- Where is the surfer at time  $t+1$ ?

- Follows a link uniformly at random

$$p(t+1) = M \cdot p(t)$$

- Suppose the random walk reaches a stationary state  $p_s$ : then  $p_s = M \cdot p_s$



- Initially, the surfer has equal probability to go to anywhere on the graph
- At each step, the surfer updates the probabilities depending on the node he is at
- Repeat this till convergence

### Page Rank with teleport

- Motivation: page rank may not converge due to:
  - Dead Ends: The surfer will always stay here, and other nodes will have 0 probability. There is convergence.
  - Spider Traps: Cycle. Random walk cannot escape the cycle. No convergence.
  - Both will cause leaking out of important values
- At each time stamp, the surfer can either
  - Follow a link (need to factor in the probability for the link too) with probability  $\beta$
  - Jump to some random page with probability  $1 - \beta$
  - Common  $\beta$  value is 0.8 or 0.9
- If we are at spider trap, we will eventually escape
- Dead end: we will always teleport!

$$\mathbf{M} = \begin{bmatrix} y & a & m \\ a & y & m \\ m & m & y \end{bmatrix} \quad \Rightarrow \quad \begin{bmatrix} y & a & m \\ a & y & m \\ m & m & y \end{bmatrix}$$

### Updated formulation:

$$\mathbf{M} = \begin{bmatrix} y & a & m \\ a & y & m \\ m & m & y \end{bmatrix} \quad \Rightarrow \quad \begin{bmatrix} y & a & m \\ a & y & m \\ m & m & y \end{bmatrix}$$

- Chances that someone surfs from connected nodes + chances that someone randomly teleports to the node

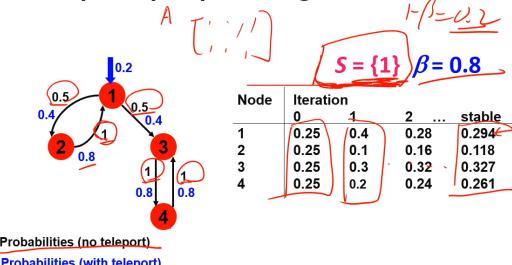
### Issues with page rank

- Measures generic popularity based on specific topics
- soln: Topic Specific Page Rank
- Uses a single measure of importance
- soln: hubs-and-authorities (other models of importance)
- Susceptible to link spam
- soln: Trust Rank artificial link topologies created to boost page rank

### Topic Specific Page Rank

- $A_{ij} = \begin{cases} \beta M_{ij} + (1 - \beta)/|S| & \text{if } i \in S \\ \beta M_{ij} + 0 & \text{otherwise} \end{cases}$
- $A$  is stochastic!
- We weighted all pages in the teleport set  $S$  equally
  - Could also assign different weights to pages!
- Teleport can only go to a relevant subset (teleport set) of pages relevant to the looker's interest

- S is the set of pages in the relevant set

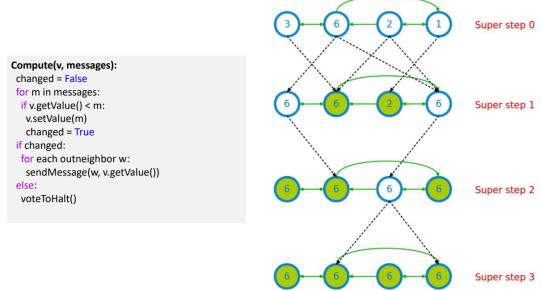


- Node 1 has the highest probability since all the nodes in the teleport set points to it

### Characteristics of Graph Algorithms

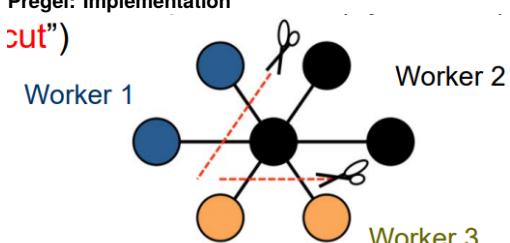
- Local computation at each vertex
- Pass message to outdegrees
- Algorithms are implemented from the point of view of a single vertex

### Pregel: Computation Model



- Computation consists of supersteps
- In each superstep, the framework invokes user-defined compute() for each vertex in parallel
- Compute()** at vertex v and superstep s
  - Read message sent to v at s-1
  - Send messages to neighbors at s + 1
  - Read or write value of v and the value of its outgoing edges (or add remove edges)
- Termination: Computation halts if all vertices are inactive
- Can be woken up

### Pregel: Implementation



- Master and Worker Architecture
- Vertices are hash partitioned and assigned to workers (edge cut)
- Worker maintains the state of its portion in memory
- Computation happens in memory
- At every superstep, each worker loops through its vertices and calls compute

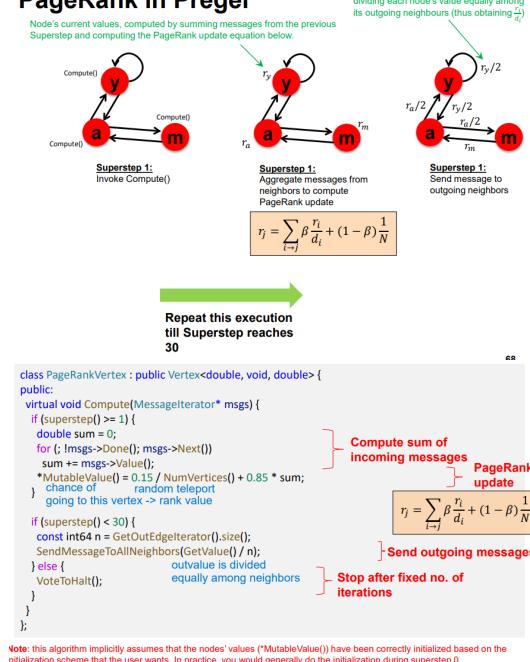
- Messages from vertices can be sent to the same or different worker (buffered locally and sent as a batch to reduce network traffic)

### Fault Tolerance

- Checkpointing to persistent storage
- Failure detected through heartbeats
- Corrupt workers are reassigned and reloaded from checkpoints

### Pregel: Page Rank

#### PageRank in Pregel



### Pregel: Spark

#### Spark Implementation on weighted pagerank

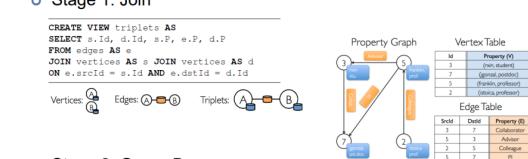
- weighted page rank algorithm:  $PR = 0.15 + 0.85 * \text{sum}(PR * \text{weight})$
- Stage 1: Join

```

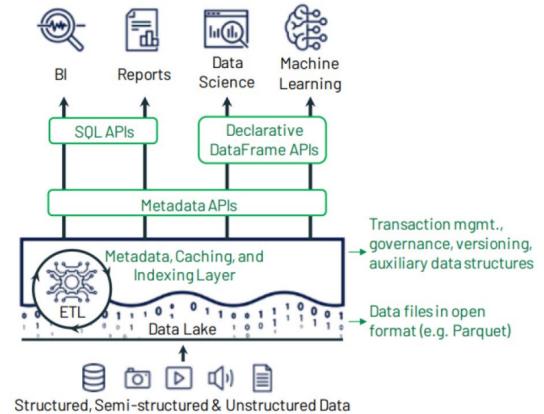
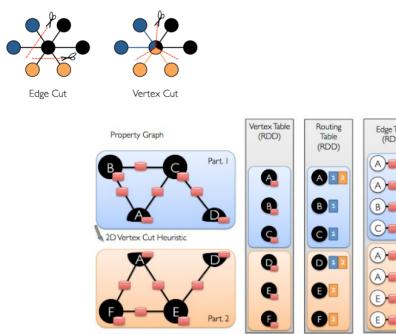
CREATE VIEW triplets AS
SELECT t.id, t.dId, s.P, d.P
FROM edges AS t
JOIN vertices AS s
JOIN vertices AS d
ON s.eId = t.sId AND e.eId = d.dId
    
```

- Stage 2: Group-By
- ```

SELECT t.dId, 0.15+0.85*sum(t.srcP*t.eP)
FROM triplets AS t GROUP BY t.dId
    
```



### Spark uses Vertex Cut to partition the graph



- Combines data lake and warehouse
- ACID + low cost + flexibility
- Good for business insights and machine learning

### Delta Lake

- Central relational repository of integrated, historical data from multiple data sources
- Reliable, high quality, strong ACID guarantees
- However, expensive to scale out and do not support non-sql based analytics

### Data lake

#### • Storage system:

- HDFS, S3, Cloud and etc.

#### • File format:

- Structured: Parquet, ORC
- semi-structured: JSON
- unstructured formats: text, images, audio, video

#### • Computing / Processing engine(s):

- batch processing engine: Spark, Presto, Apache Hive
- stream processing engine: Spark, Apache Flink
- machine learning library: Spark MLlib, scikit-learn, R

### Delta Lake Format

| Step           | Code                                                                                                                                                                                                                                                  | Parquet files Written | JSON files in _delta_log |
|----------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|--------------------------|
| Read 00.json   | # Create vertex     vertex.create();     # Write format(delta)     vertex.writeFormat("delta");     # Save path     vertex.save(DATALAKE_PATH)                                                                                                        | part0.parquet         | part0.json               |
| Include part-0 | # Include part-0                                                                                                                                                                                                                                      | part1.parquet         | part0.json               |
| Include part-1 | # Include part-1                                                                                                                                                                                                                                      | part2.parquet         | part0.json               |
| Read 01.json   | # Read vertex     vertex.readFormat("delta");     # Include part-2     vertex.includePart(2);     # Write format(delta)     vertex.writeFormat("delta");     # Save path     vertex.save(DATALAKE_PATH)                                               | part3.parquet         | part0.json               |
| Include part-2 | # Include part-2                                                                                                                                                                                                                                      | part4.parquet         | part0.json               |
| Read 02.json   | # Read vertex     vertex.readFormat("delta");     # Remove part-0     vertex.removePart(0);     # Include part-3     vertex.includePart(3);     # Write format(delta)     vertex.writeFormat("delta");     # Save path     vertex.save(DATALAKE_PATH) | part5.parquet         | part0.json               |
| Include part-3 | # Include part-3                                                                                                                                                                                                                                      | part6.parquet         | part0.json               |
| Final result:  | part1, part2, part3                                                                                                                                                                                                                                   |                       |                          |
|                | are included in latest data                                                                                                                                                                                                                           |                       |                          |
|                | without this new log, the commit didn't happen                                                                                                                                                                                                        |                       |                          |
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| Step | Code                                                                                                                                                                                                                                                                                                                                                                                                               | Parquet Files Written                                                 | JSON files in _delta_log                                                                                                                                                    |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1    | <pre>df<br/>.coalesce(1)<br/>.write<br/>.format("delta")<br/>.save(DATALAKE_PATH)</pre>                                                                                                                                                                                                                                                                                                                            | part-00000.parquet                                                    | Action Part Name<br>Add part-00000<br>00000.json                                                                                                                            |
| 2    | <pre># Loop from 0..9<br/>for index in range(9):<br/><br/>    # create a patient tuple<br/>    patientId = 10 + index<br/>    t = (patientId,<br/>        f"Patient {patientId}",<br/>        "Phoenix")<br/><br/>    # create and write the dataframe<br/>    df = spark.createDataFrame(<br/>        [t], columns)<br/>    df<br/>.write<br/>.format("delta")<br/>.mode("append")<br/>.save(DATALAKE_PATH)</pre> | part-00001.parquet<br>part-00002.parquet<br>...<br>part-00009.parquet | Action Part Name<br>Add part-00001<br>00001.json<br><br>Action Part Name<br>Add part-00002<br>00002.json<br><br>...<br><br>Action Part Name<br>Add part-00009<br>00009.json |
| 3    | <pre>patientId = 100<br/>t = (patientId, "Patient<br/>(patientId)", "Phoenix")<br/><br/>df = spark.createDataFrame(<br/>    [t], columns)<br/>df<br/>.write<br/>.format("delta")<br/>.mode("append")<br/>.save(DATALAKE_PATH)</pre>                                                                                                                                                                                | part-00010.parquet                                                    | Action Part Name<br>Add part-00010<br>00010.json<br><br>00010.checkpoint.parquet                                                                                            |
| 4    | <pre>for index in range(2):<br/>    patientId = 200 + index<br/>    t = (patientId,<br/>        f"Patient {patientId}",<br/>        "Phoenix")<br/><br/>    df = spark.createDataFrame(<br/>        [t], columns)<br/>    df<br/>.write<br/>.format("delta")<br/>.mode("append")<br/>.save(DATALAKE_PATH)</pre>                                                                                                    | part-00012.parquet<br>part-00013.parquet                              | Action Part Name<br>Add part-00012<br>00001.json<br><br>Action Part Name<br>Add part-00013<br>00002.json                                                                    |

- Standard parquet file with additional metadata
- Uses delta log as a single source of truth and enables concurrent read and writes and atomic transactions and commits
- After 10 JSON files (logs), the logs are checkpointed to reduce the number of logs read and support fault tolerance