Introduction to Data Stream Processing

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Motivation

- Many applications must process large streams of live data and provide results in real-time.
    - Wireless sensor networks
    - Traffic management applications
    - Stock marketing
    - Environmental monitoring applications
    - Fraud detection tools
    - ...

Stream Processing Systems

- Database Management Systems (DBMS): data-at-rest analytics
  - Store and index data before processing it.
  - Process data only when explicitly asked by the users.

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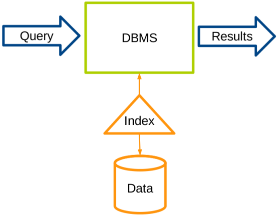
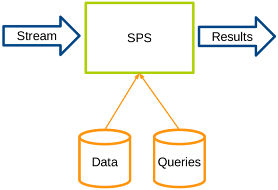
  - Store and index data before processing it.
  - Process data only when explicitly asked by the users.
- Stream Processing Systems (SPS): data-in-motion analytics
  - Processing information as it flows, without storing them persistently.

DBMS vs. SPS

- DBMS
  - Persistent data where updates are relatively infrequent.
  - Runs queries just once to return a complete answer.

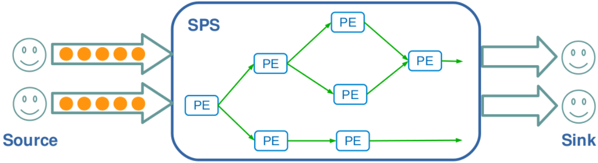
- SPS
  - Transient data that is continuously updated.
  - Executes standing queries, which run continuously and provide updated answers as new data arrives.





SPS Data Model

- Data stream is unbound and broken into a sequence of individual data items, called tuples.
- A data tuple is the atomic data item in a data stream.
  - Similar to a database row.



SPS Data Model

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- A data tuple is the atomic data item in a data stream.
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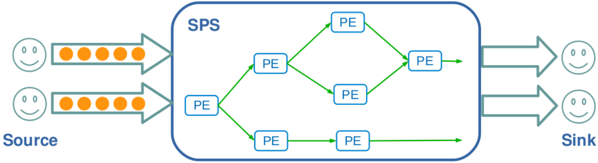
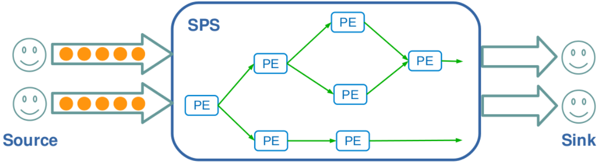
- Three classes:
  - Structured: known schema
  - Semi-structured: self-describing tags, e.g., HTML or XML
  - Unstructured: custom or proprietary formats, e.g., video, audio



SPS Processing Model

- The tuples are processed by the application's operators or processing element (PE).
- A PE is the basic functional unit in an application.
  - A PE processes input tuples, applies a function, and outputs tuples.
  - A set of PEs and stream connections, organized into a data flow graph.



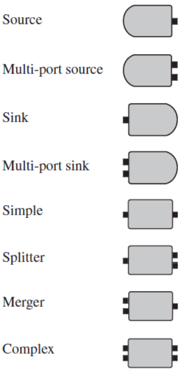
SPS Programming Model

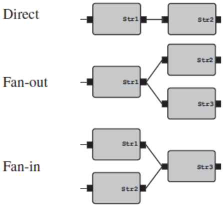
SPS Programming Model

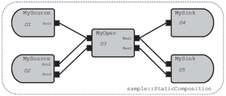
- SPS data flow programming
- Flow composition: techniques for creating the topology associated with the flow graph for an application.
- Flow manipulation: the use of PEs to perform transformations on data flows.

Data Flow Composition

Data Flow Composition







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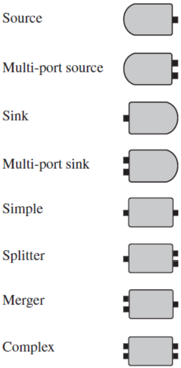

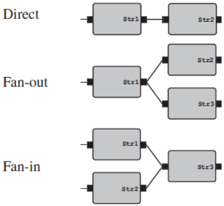

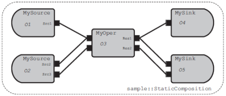

- Flow composition patterns:
  - Static composition
  - Dynamic composition
  - Nested composition

Static Flow Composition

- Creating the parts of the application topology that are known at development time.

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- Example:
  - The input stream from Twitter feed.
  - The analysis PE probes the messages for positive or negative tone.
  - The connection between the source and the analysis PE is known at development time.
  - Explicitly connecte the output port of the source PE to the input port of the analysis PE.

Dynamic Flow Composition

- Creating the segments of an application topology that are not fully known at development time.

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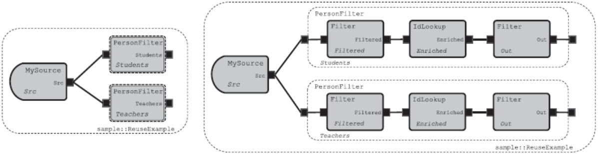
- Example:
  - An application with an analysis PE that can consume multiple input streams.
  - The input sources are dynamic (appear and disappear).
  - The connection between the analysis PE and sources can be specified implicitly at development time.

Nested Flow Composition

- Addresses the modularity problem in large scale flow graphs.
- Group a subset of the flow graph as a regular PE.
- Producing smaller and more manageable views of the overall data flow graph.



Data Flow Manipulation

Data FLow Manipulation

- How the streaming data is manipulated by the different PE instances in the flow graph?
- PEs properties:
  - PEs tasks
  - PEs states
  - Windowing
  - Selectivity and arity

PEs Tasks (1/2)

- Edge adaptation: converting data from external sources into tuples that can be consumed by downstream PEs.

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- Aggregation: collecting and summarizing a subset of tuples from one or more streams.
- Splitting: partitioning a stream into multiple streams.
- Merging: combining multiple input streams.

PEs Tasks (2/2)

- Logical and mathematical operations: applying different logical processing, relational processing, and mathematical functions to tuple attributes.

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- Sequence manipulation: reordering, delaying, or altering the temporal properties of a stream.
- Custom data manipulations: applying data mining, machine learning, ...

PEs States (1/3)

- A PE can either maintain internal state across tuples while processing them, or process tuples independently of each other.
- Stateful vs. stateless tasks

PEs States (2/3)

- Stateless tasks: do not maintain state and process each tuple independently of prior history, or even from the order of arrival of tuples.

PEs States (2/3)

- Stateless tasks: do not maintain state and process each tuple independently of prior history, or even from the order of arrival of tuples.
- Easily parallelized.
- No synchronization in a multi-threaded context.
- Restart upon failures without the need of any recovery procedure.

PEs States (3/3)

- Stateful tasks: involves maintaining information across different tuples to detect complex patterns.

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- Stateful tasks: involves maintaining information across different tuples to detect complex patterns.
- A PE is usually a synopsis of the tuples received so far.
- A subset of recent tuples kept in a window buffer.

Windowing (1/3)

- Window: a buffer associated with an input port to retain previously received tuples.

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  - For example by a property of the window, e.g., buffer's capacity.

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- Eviction policy: determines the properties of the tuples that can be held in the buffer.
    - For example by a property of the window, e.g., buffer's capacity.
- Trigger policy: determines how often the data buffered in the window gets processed by the operator internal logic.

Windowing (2/3)

- Four different windowing management policies.
- Count-based policy: characterized by the maximum number of tuples a window buffer can hold
- Delta-based policy: specified using a delta threshold value and a tuple attribute.
- Time-based policy: specified using a wall-clock time period.
- Punctuation-based policy: a window buffer becomes ready for processing every time a punctuation is received.

Windowing (3/3)

- Two types of windows: tumbling and sliding
  - Both store tuples in the order they arrive.
  - They differ in the eviction and trigger policies.

- Tumbling window: supports batch operations.
  - When the buffer fills up, all the tuples are evicted.

- Sliding window: supports incremental operations.
  - When the buffer fills up, older tuples are evicted.

Selectivity and Arity

- Selectivity: the relationship between the number of tuples produced and the number of tuples it ingested.
    - Fixed and variable

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- Selectivity: the relationship between the number of tuples produced and the number of tuples it ingested.
  - Fixed and variable
- Arity: the number of ports an operator has.
  - One-to-one (1:1)
  - One-to-at-most-one (1:[0, 1])
  - One-to-many (1:N)
  - Many-to-one (M:1)
  - Many-to-many (M:N)

SPS Runtime System

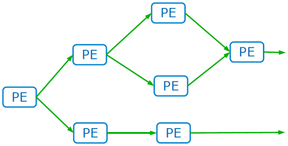
Job and Job Management

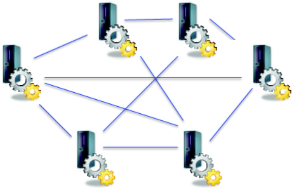
- At runtime, an application is represented by one or more jobs.
- Jobs are deployed as a collection of PEs.
- Job management component must identify and track individual PEs, the jobs they belong to, and associate them with the user that instantiated them.

Logical Plan vs. Physical Plan (1/3)

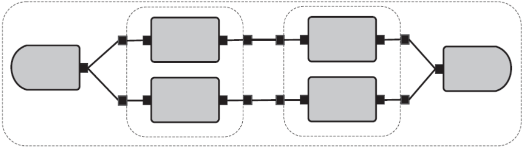
- **Logical plan**: a data flow graph, where the vertices correspond to PEs, and the edges to stream connections.

- **Physical plan**: a data flow graph, where the vertices correspond to OS processes, and the edges to transport connections.

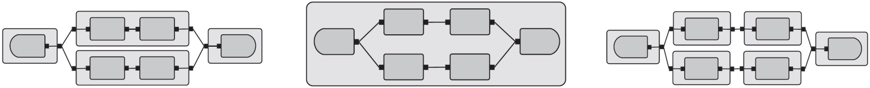




Logical Plan vs. Physical Plan (2/3)



Logical plan



Different physical plans

Logical Plan vs. Physical Plan (3/3)

- How to map a network of PEs onto the physical network of nodes?
  - Parallelization
  - Fault tolerance
  - Optimization

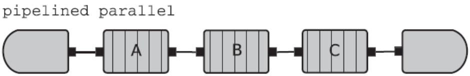
Parallelization

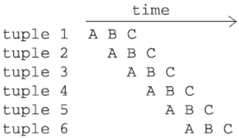
Parallelization

- How to scale with increasing the number queries and the rate of incoming events?
- Three forms of parallelisms.
  - Pipelined parallelism
  - Task parallelism
  - Data parallelism

Pipelined Parallelism

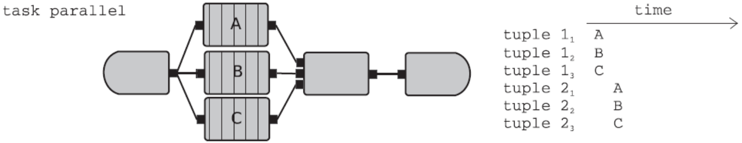
- Sequential stages of a computation execute concurrently for different data items.





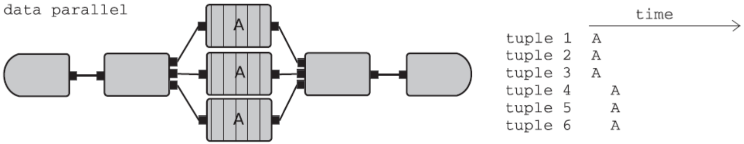
Task Parallelism

- Independent processing stages of a larger computation are executed concurrently on the same or distinct data items.



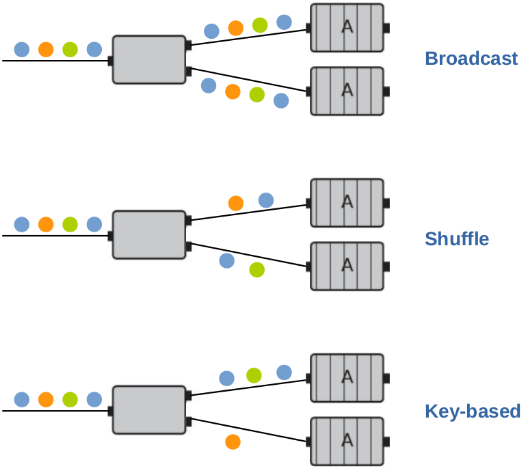
Data Parallelism (1/2)

- The same computation takes place concurrently on different data items.



Data Parallelism (2/2)

- How to allocate data items to each computation instance?



Fault Tolerance

Recovery Methods (1/2)

- The recovery methods of streaming frameworks must take:
  - Correctness, e.g., data loss and duplicates
  - Performance, e.g., low latency

Recovery Methods (2/2)

- GAP recovery
- Rollback recovery
- Precise recovery

GAP Recovery (Cold Restart)

- The weakest recovery guarantee
- A new task takes over the operations of the failed task.
- The new task starts from an empty state.
- Tuples can be lost during the recovery phase.

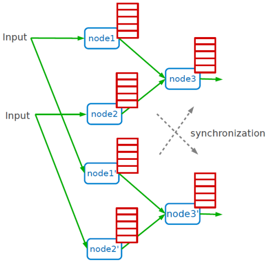
Rollback Recovery

- The information loss is avoided, but the output may contain duplicate tuples.

- Three types of rollback recovery:
  - Active backup
  - Passive backup
  - Upstream backup

Rollback Recovery - Active Backup

- Each processing node has an associated backup node.
- Both primary and backup nodes are given the same input.
- The output tuples of the backup node are logged at the output queues and they are not sent downstream.
- If the primary fails, the backup takes over by sending the logged tuples to all downstream neighbors and then continuing its processing.



Rollback Recovery - Passive Backup

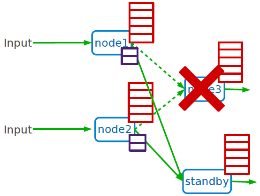
- Periodically check-points processing state to a shared storage.
- The backup node takes over from the latest checkpoint when the primary fails.
- The backup node is always equal or behind the primary.

Rollback Recovery - Upstream Backup

- Upstream nodes store the tuples until the downstream nodes acknowledge them.

- If a node fails, an empty node rebuilds the latest state of the failed primary from the logs kept at the upstream server.

- There is no backup node in this model.



Precise Recovery

- Post-failure output is exactly the same as the output without failure.

- Can be achieved by modifying the algorithms for rollback recovery.
  - For example, in passive backup, after a failure occurs the backup node can ask the downstream nodes for the latest tuples they received and trim the output queues accordingly to prevent the duplicates.

Optimization

Performance Optimization

- Data sources continuously producing the data.
- Applications must keep up with the rate of the input data they process.
- Optimization techniques:
  - Early data volume reduction
  - Redundancy elimination
  - Operator fusion
  - Tuple batching
  - Load balancing
  - Load shedding

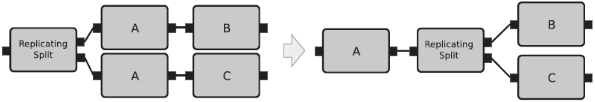
Early Data Volume Reduction

- Reducing the data volume as early as possible.
  - Sampling, filtering, quantization, projection, and aggregation.

- Operator reordering
  - Executing the computationally cheaper operator and/or the more selective operator earlier reduces the overall cost.

Redundancy Elimination

- Removing the redundant segments from a data flow graph.

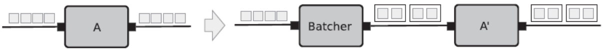


Operator Fusion

- It changes only the physical layout.
- If two operators of the two ends of a stream connection are placed on different hosts: non-negligible network cost
- But, if these two operators are fused inside a single PE in the same host: the direct call is used
- Operator fusion can be effective if the per-tuple processing cost of the operators being fused is low compared to the cost of transferring the tuples across the stream connection.

Tuple Batching

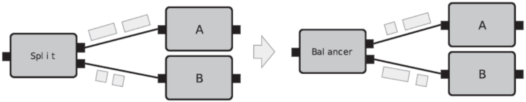
- Processing a group of tuples in every iteration of an operator's internal algorithm.
- Can increase the throughput at the expense of higher latency.



Load Balancing

- Flow partitioning to distribute the workload, e.g., data or task parallelism.

- Distributing the load evenly across the different subflows.



Load Shedding

- Used by an operator to reduce the amount of computational resources it uses.
  - Sidesteping sustained increases in memory utilization.
  - Limiting the amount of work an operator performs per unit of time: decrease the operator latency, and improve the throughput.

- Different techniques: dropping incoming tuples, data reduction techniques (e.g., sampling), ...

Distributed Messaging System

What is Messaging? (1/2)

- Suppose you have a website, and every time someone loads a page, you send a user viewed page event to a messaging system.

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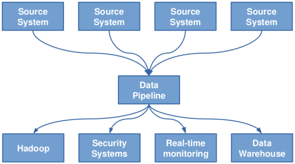
- A messaging system lets you decouple all of this work from the actual web page serving.



What is Messaging? (2/2)

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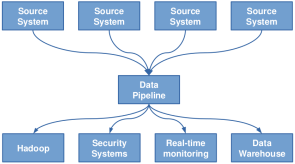
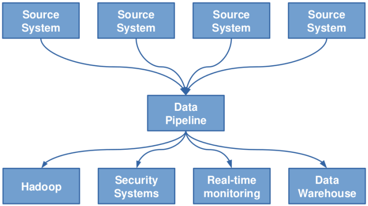
- Messages can be added to the messaging systems when something happens.
- Consumers read messages from these systems, and process them or take actions based on the message contents.



Existing Messaging Systems

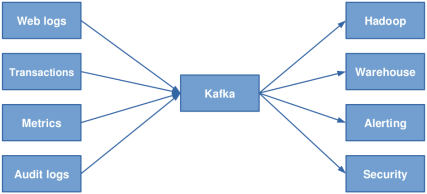
- Message queues: ActiveMQ and RabbitMQ
- Pub/Sub systems: Kafka and Kestrel
- Log aggregation systems: Flume and Scribe



Kafka

Kafka (1/6)

- Kafka is a distributed, topic oriented, partitioned, replicated commit log service.



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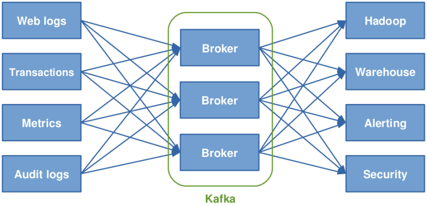

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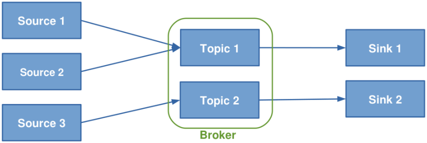

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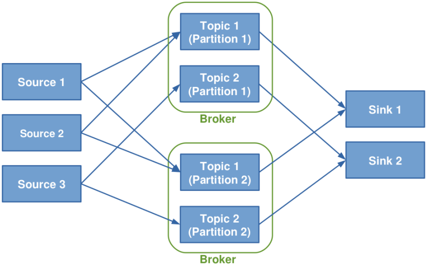

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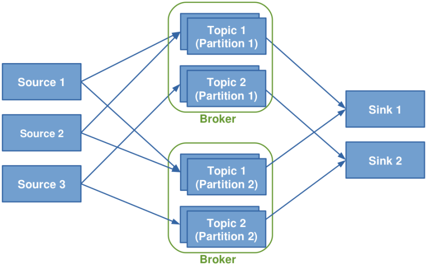
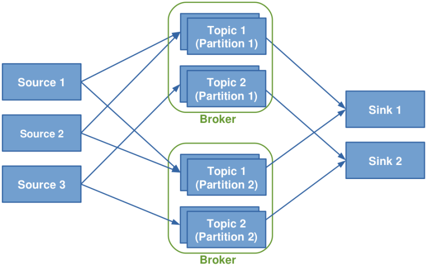


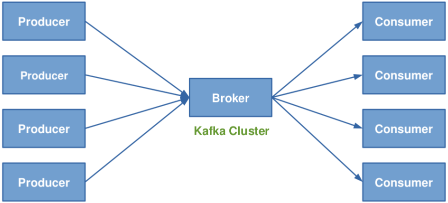
Kafka (6/6)

- Kafka is also a pub-sub messaging system.



Kafka Basic Messaging Terminology

- Kafka maintains feeds of messages in categories called topics.



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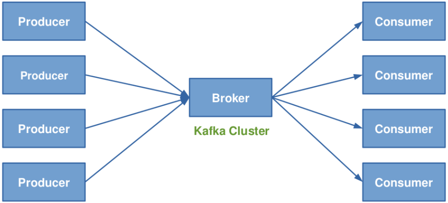

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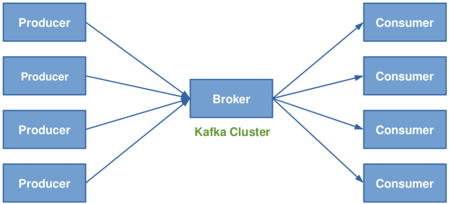
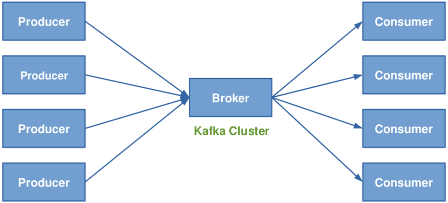
- Kafka maintains feeds of messages in categories called topics.
- Processes that publish messages to a Kafka topic called producers.
- Processes that subscribe to topics and process the feed of published messages called consumers.



Kafka Basic Messaging Terminology

- Kafka maintains feeds of messages in categories called topics.
- Processes that publish messages to a Kafka topic called producers.
- Processes that subscribe to topics and process the feed of published messages called consumers.
- Kafka is run as a cluster comprised of one or more servers each of which is called a broker.



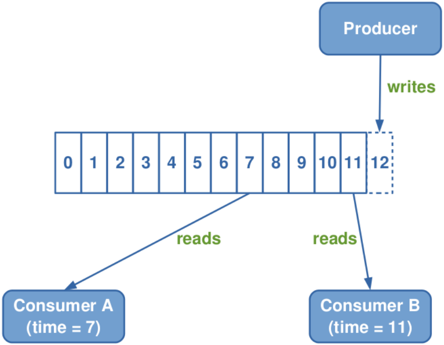
Logs, Topics and Partition (1/5)

- Kafka is about logs.
- Topics are queues: a stream of messages of a particular type

```
jkreps-mn:~ jkreps$ tail -f -n 20 /var/log/apache2/access_log
::1 - - [23/Mar/2014:15:07:00 -0700] "GET /images/apache_feather.gif HTTP/1.1" 200 4128
::1 - - [23/Mar/2014:15:07:04 -0700] "GET /images/producer_consumer.png HTTP/1.1" 200 8
::1 - - [23/Mar/2014:15:07:04 -0700] "GET /images/log_anatomy.png HTTP/1.1" 200 19579
::1 - - [23/Mar/2014:15:07:04 -0700] "GET /images/consumer-groups.png HTTP/1.1" 200 268
::1 - - [23/Mar/2014:15:07:04 -0700] "GET /images/log_compaction.png HTTP/1.1" 200 4141
::1 - - [23/Mar/2014:15:07:04 -0700] "GET /documentation.html HTTP/1.1" 200 189893
::1 - - [23/Mar/2014:15:07:04 -0700] "GET /images/log_cleaner_anatomy.png HTTP/1.1" 200
::1 - - [23/Mar/2014:15:07:04 -0700] "GET /images/kafka_log.png HTTP/1.1" 200 134321
::1 - - [23/Mar/2014:15:07:04 -0700] "GET /images/mirror-maker.png HTTP/1.1" 200 17054
::1 - - [23/Mar/2014:15:08:07 -0700] "GET /documentation.html HTTP/1.1" 200 189937
::1 - - [23/Mar/2014:15:08:07 -0700] "GET /styles.css HTTP/1.1" 304 -
::1 - - [23/Mar/2014:15:08:07 -0700] "GET /images/kafka_logo.png HTTP/1.1" 304 -
::1 - - [23/Mar/2014:15:08:07 -0700] "GET /images/producer_consumer.png HTTP/1.1" 304 -
::1 - - [23/Mar/2014:15:08:07 -0700] "GET /images/log_anatomy.png HTTP/1.1" 304 -
::1 - - [23/Mar/2014:15:08:07 -0700] "GET /images/consumer-groups.png HTTP/1.1" 304 -
::1 - - [23/Mar/2014:15:08:07 -0700] "GET /images/log_cleaner_anatomy.png HTTP/1.1" 304
::1 - - [23/Mar/2014:15:08:07 -0700] "GET /images/log_compaction.png HTTP/1.1" 304 -
::1 - - [23/Mar/2014:15:08:07 -0700] "GET /images/kafka_log.png HTTP/1.1" 304 -
::1 - - [23/Mar/2014:15:08:07 -0700] "GET /images/mirror-maker.png HTTP/1.1" 304 -
::1 - - [23/Mar/2014:15:09:55 -0700] "GET /documentation.html HTTP/1.1" 200 195264
```

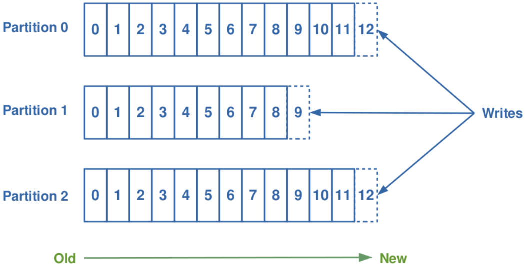
Logs, Topics and Partition (2/5)

- Each message is assigned a sequential id called an offset.



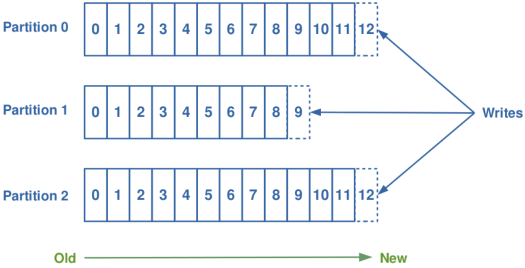
Logs, Topics and Partition (3/5)

- Topics are logical collections of partitions (the physical files).
  - Ordered
  - Append only
  - Immutable



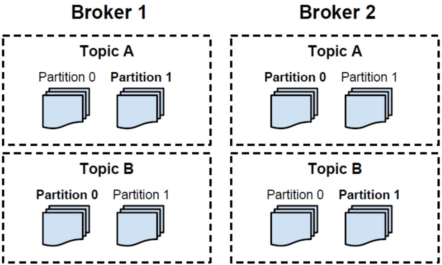
Logs, Topics and Partition (4/5)

- Ordering is only guaranteed within a partition for a topic.
- Messages sent by a producer to a particular topic partition will be appended in the order they are sent.
- A consumer instance sees messages in the order they are stored in the log.

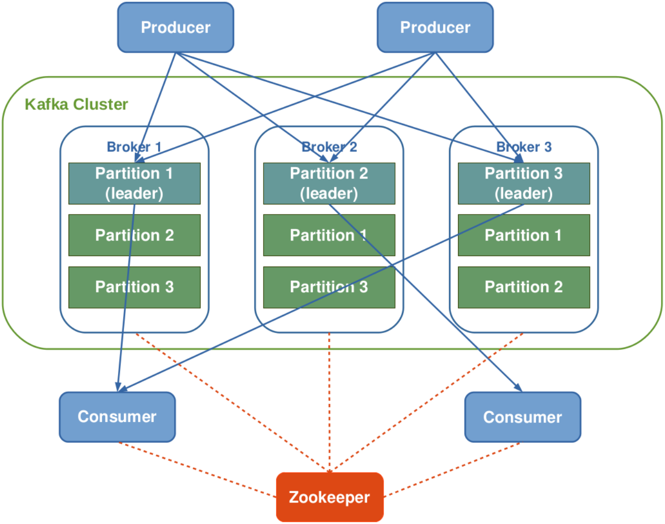


Logs, Topics and Partition (5/5)

- Partitions of a topic are replicated: fault-tolerance
- A broker contains some of the partitions for a topic.
- One broker is the leader of a partition: all writes and reads must go to the leader.



Kafka Architecture

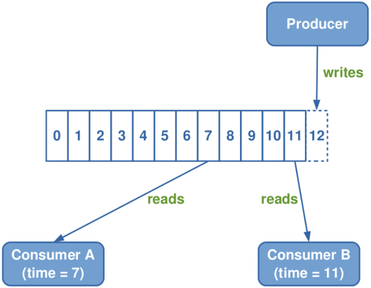


Producers

- Producers publish data to the topics of their choice.
- Producers are responsible for choosing which message to assign to which partition within the topic.
  - Round-robin
  - Key-based

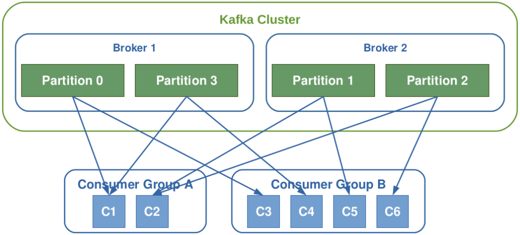
Consumers and Consumer Groups (1/3)

- Consumers pull a range of messages from brokers.
- Multiple consumers can read from same topic on their own pace.
- Consumers maintain the message offset.



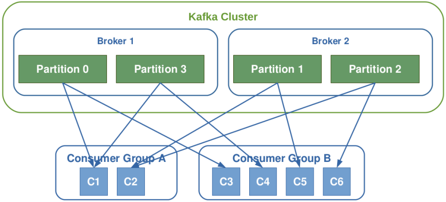
Consumers and Consumer Groups (2/3)

- Consumers can be organized into consumer groups.
- Each message is delivered to only one of the consumers within the group.
- All messages from one partition are consumed only by a single consumer within each consumer group.
  - A partition is in a topic the smallest unit of parallelism.



Consumers and Consumer Groups (3/3)

- If all consumers instances are in one group: a traditional queue with load balancing
- If all consumers instances are in different groups: all messages are broadcast to all consumer instances
- If many consumers are instances in a group: each consumer instance reads from one or more partitions for a topic



Brokers

- The published messages are stored at a set of servers called brokers.
- Brokers are sateless.
- Messages are kept on log for predefined period of time.

Coordination

- Kafka uses Zookeeper for the following tasks:
- Detecting the addition and the removal of brokers and consumers.
- Triggering a rebalance process in each consumer when the above events happen.
- Maintaining the consumption relationship and keeping track of the consumed offset of each partition.

Delivery Guarantees

- Kafka guarantees that messages from a single partition are delivered to a consumer in order.
- There is no guarantee on the ordering of messages coming from different partitions.
- Kafka only guarantees at-least-once delivery.
- No exactly-once delivery: two-phase commits

Summary

Summary

- SPS vs. DBMS
- Data stream, unbounded data, tuples
- PEs and dataflow
- SPS programming languages: declarative, imperative, pattern-based, visualized
- SPS data flow: composiation and manipulation
- SPS runtime: parallelization, fault-tolerance, optimization

Summary

- Messaging system: decoupling
- Kafka: distributed, topic oriented, partitioned, replicated log service
- Logs, topcs, partition
- Kafka architecture: producer, consumer (groups), broker, coordinator

Questions?

References

- H. Andrade et al., Fundametal of Stream Processing
  - Sections 1, 2, 3, 4, 5, 7, and 9