Introduction to Data Stream Processing

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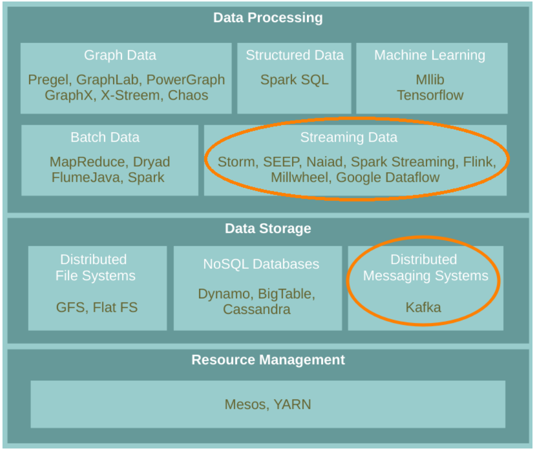
The Course Web Page

`https://id2221kth.github.io`

The Questions-Answers Page

https://tinyurl.com/bdenpwc5

Where Are We?

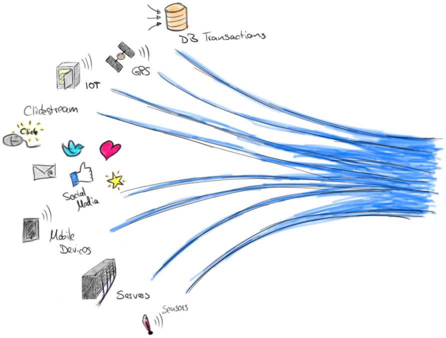

Data Processing
Graph Data
Pregel, GraphLab, PowerGraph
GraphX, X-Streem, Chaos
Structured Data
Spark SQL
Machine Learning
Mllib
Tensorflow
Batch Data
MapReduce, Dryad
FlumeJava, Spark
Streaming Data
Storm, SEEP, Naiad, Spark Streaming, Flink,
Millwheel, Google Dataflow
Data Storage
Distributed
File Systems
GFS, Flat FS
NoSQL Databases
Dynamo, BigTable,
Cassandra
Distributed
Messaging Systems
Kafka
Resource Management
Mesos, YARN

Stream Processing (1/3)

- Stream processing is the act of continuously incorporating new data to compute a result.

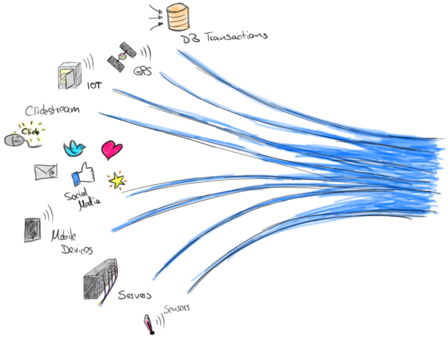
Stream Processing (2/3)

- The input data is unbounded.
  - A series of events, no predetermined beginning or end.



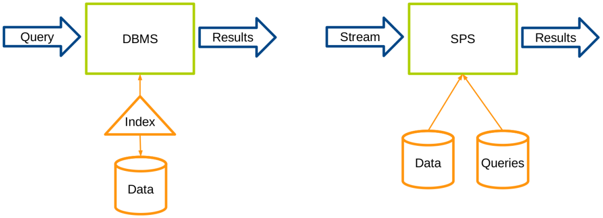
Stream Processing (2/3)

- The input data is unbounded.
  - A series of events, no predetermined beginning or end.
  - E.g., credit card transactions, clicks on a website, or sensor readings from IoT devices.



Stream Processing (3/3)

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



Stream Processing (3/3)

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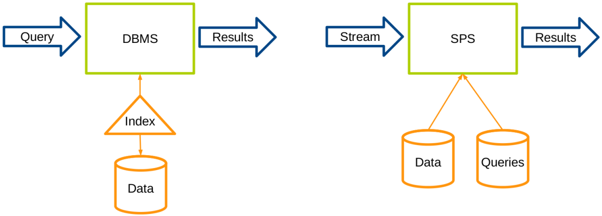
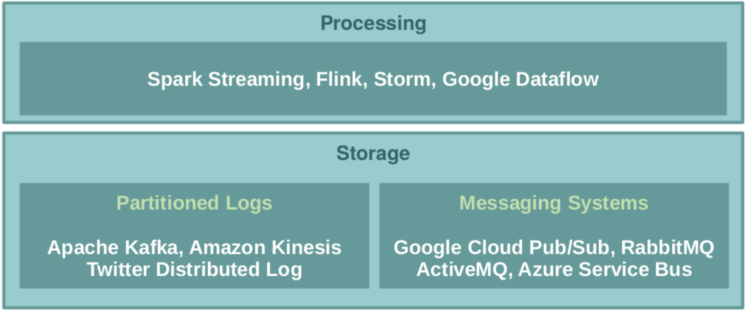
- Stream Processing Systems (SPS): data-in-motion analytics
  - Processing information as it flows, without storing them persistently.



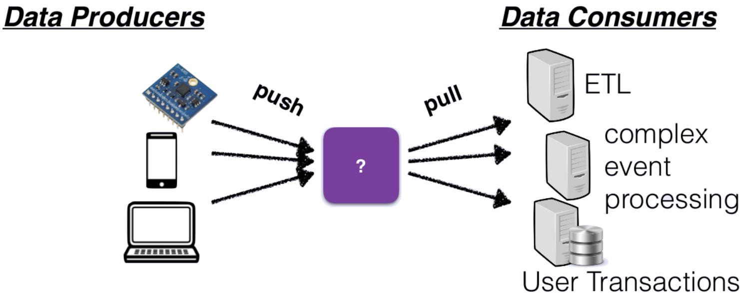
Stream Processing Systems Stack



Data Stream Storage

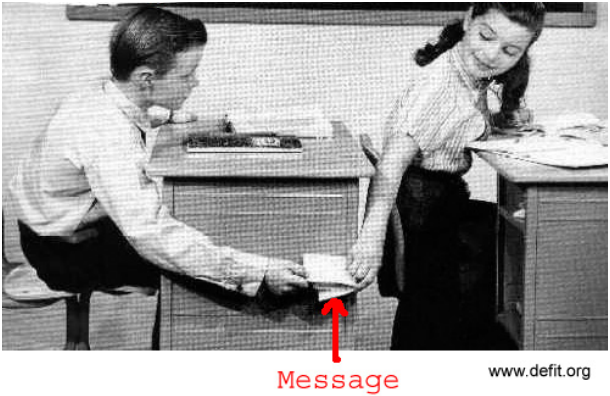
The Problem

- We need disseminate streams of events from various producers to various consumers.



Possible Solution?

- Messaging systems



What is Messaging System?

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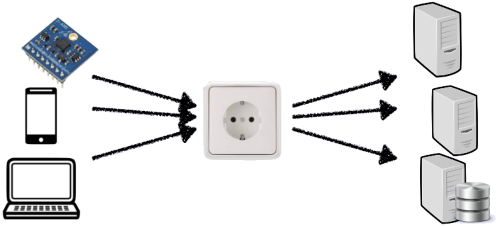
- Messaging systems
  - Direct messaging
  - Message brokers

Direct Messaging (1/2)

- Necessary in latency critical applications (e.g., remote surgery).
- A producer sends a message containing the event, which is pushed to consumers.



Direct Messaging (1/2)

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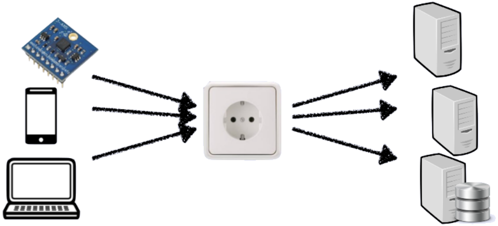
- Both consumers and producers have to be online at the same time.



Direct Messaging (2/2)

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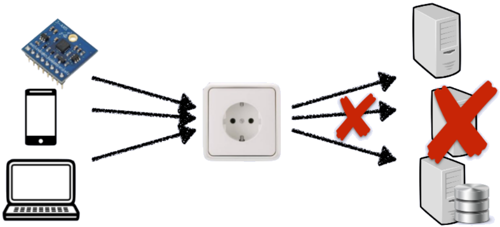

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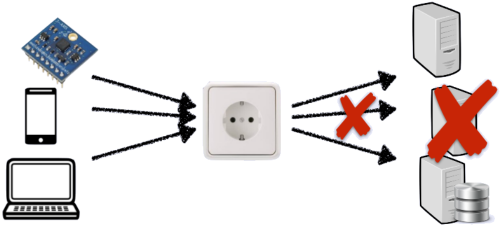

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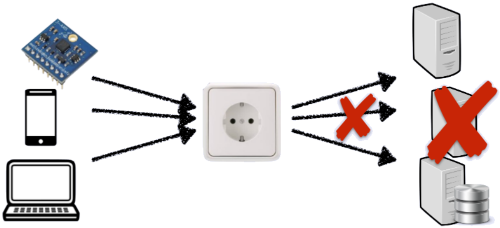

Direct Messaging (2/2)

- What happens if a consumer crashes or temporarily goes offline? (not durable)
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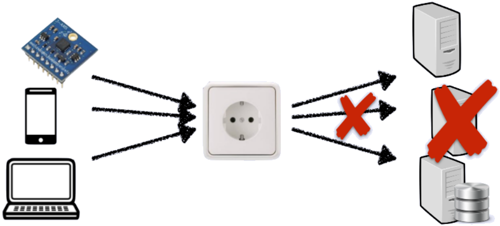
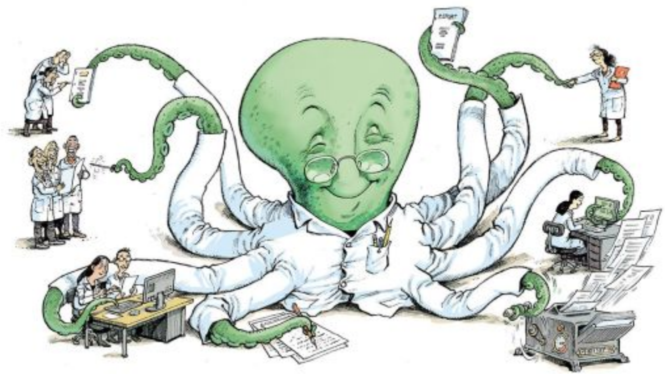
  - Backpressure
- We need message brokers that can log events to process at a later time.



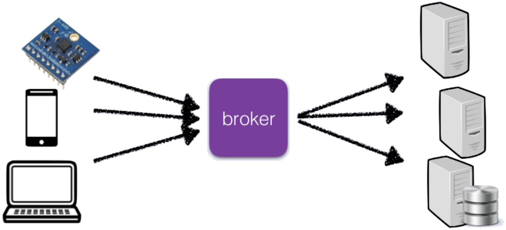
Message Broker



[https://bluesyemre.com/2018/10/16/thousands-of-scientists-publish-a-paper-every-five-days]

Message Broker

- A message broker decouples the producer-consumer interaction.
- It runs as a server, with producers and consumers connecting to it as clients.



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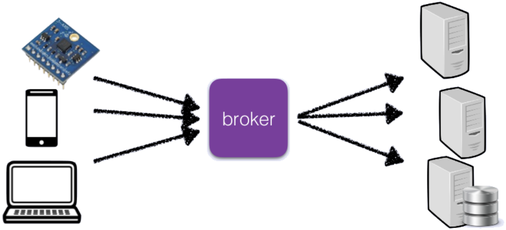

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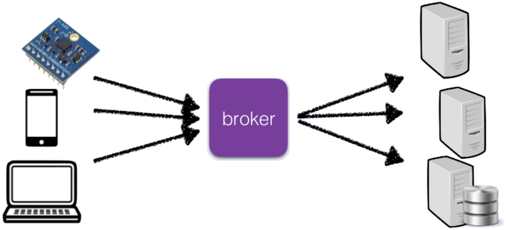
- Consumers are generally asynchronous.



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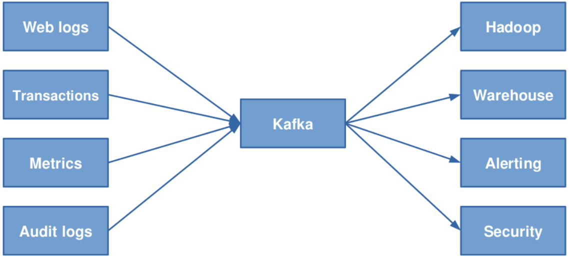
- Log-based message brokers durably store all events in a sequential log.
- A log is an append-only sequence of records on disk.
- A producer sends a message by appending it to the end of the log.
- A consumer receives messages by reading the log sequentially.

Kafka - A Log-Based Message Broker

kafka

Kafka (1/5)

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



Kafka (2/5)

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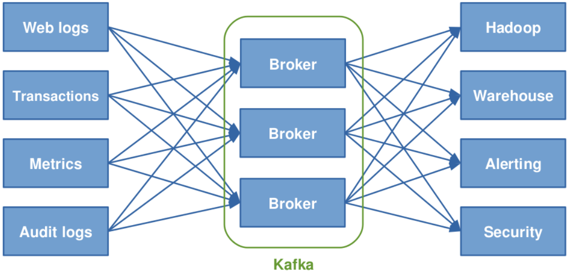

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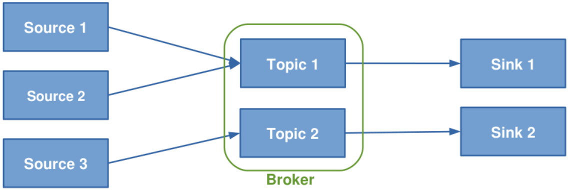

Kafka (4/5)

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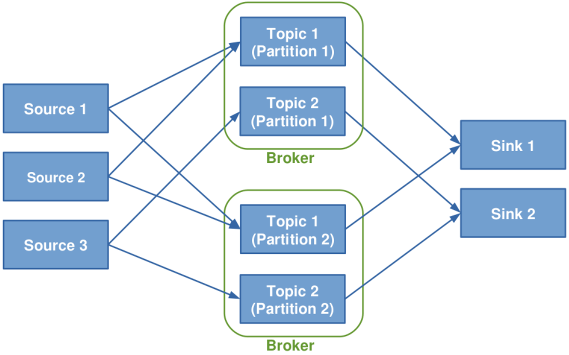

Kafka (5/5)

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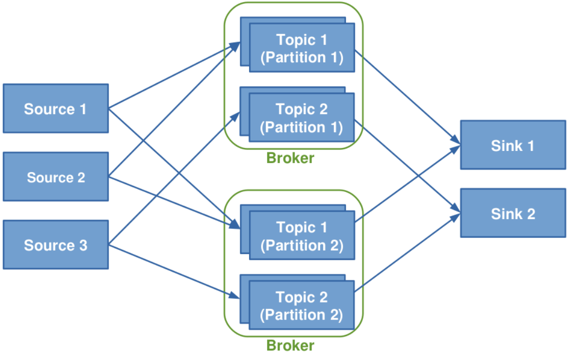

Logs, Topics and Partition (1/6)

- 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 86
::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 2682
::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 -
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::1 - - [23/Mar/2014:15:09:55 -0700] "GET /documentation.html HTTP/1.1" 200 195264
```
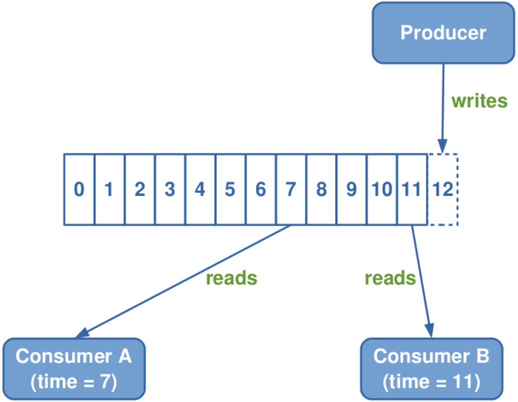
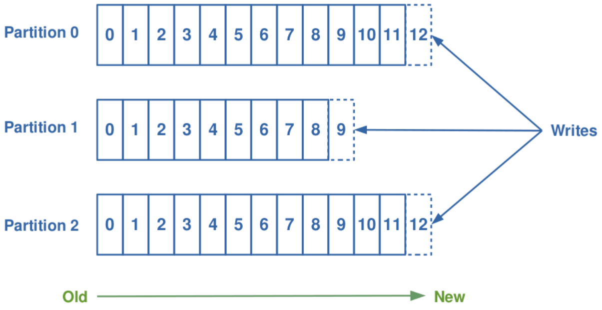

Logs, Topics and Partition (2/6)

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



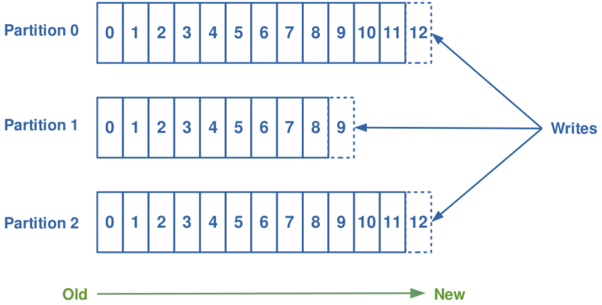
Logs, Topics and Partition (3/6)

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



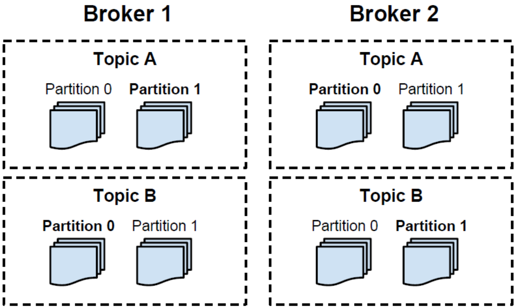
Logs, Topics and Partition (4/6)

- 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.

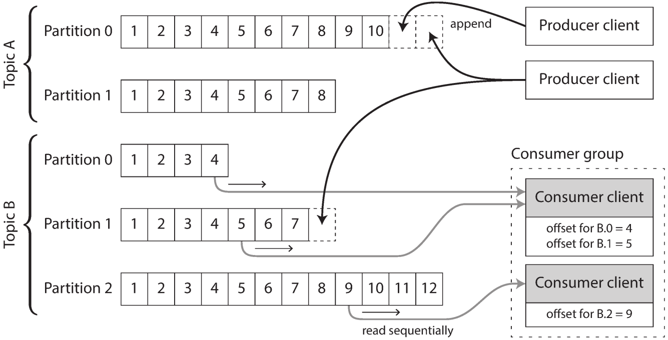


Logs, Topics and Partition (5/6)

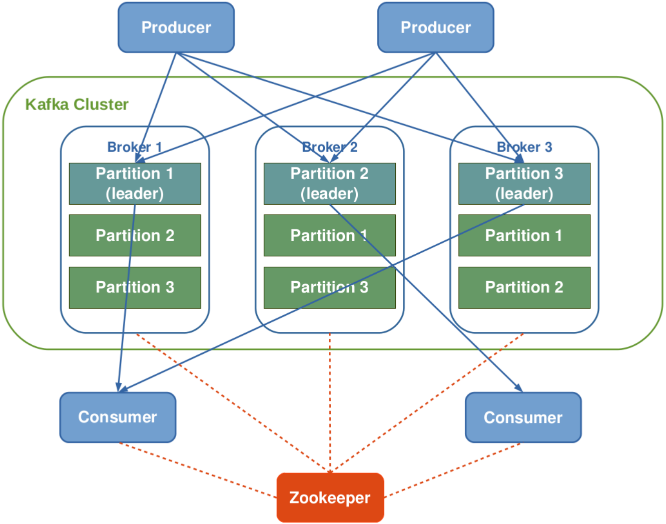
- Partitions of a topic are replicated: fault-tolerance
- A broker contains some of the partitions for a topic.
- One broker is the leader of a partition: all writes and reads must go to the leader.



Partitioned Logs (6/6)



Kafka Architecture



Coordination

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- Detecting the addition and the removal of brokers and consumers.
- Keeping track of the consumed offset of each partition.

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- Messages in queues expire based on pre-configured time periods (e.g., once a day).

Delivery Guarantees

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- There is no guarantee on the ordering of messages coming from different partitions.
- Kafka only guarantees at-least-once delivery.

Start and Work With Kafka

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zookeeper-server-start.sh config/zookeeper.properties
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```
# Consume the messages sent to the topic "avg"
kafka-console-consumer.sh --topic avg --from-beginning --bootstrap-server localhost:9092
```

Data Stream Processing

Streaming Data

- Data stream is unbound data, which is broken into a sequence of individual tuples.
- A data tuple is the atomic data item in a data stream.
- Can be structured, semi-structured, and unstructured.

Streaming Data Processing Design Points

- Continuous vs. micro-batch processing
- Record-at-a-Time vs. declarative APIs
- Event time vs. processing time
- Windowing

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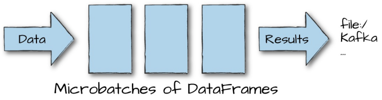
Streaming Data Processing Patterns

- Micro-batch systems
  - Batch engines
  - Slicing up the unbounded data into a sets of bounded data, then process each batch.



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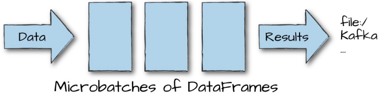
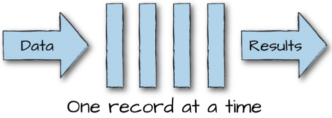


- Continuous processing-based systems
  - Each node in the system continually listens to messages from other nodes and outputs new updates to its child nodes.



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Record-at-a-Time vs. Declarative APIs

- Record-at-a-Time API (e.g., Storm)
  - Low-level API
  - Passes each event to the application and let it react.
  - Useful when applications need full control over the processing of data.
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- Declarative API (e.g., Spark streaming, Flink, Google Dataflow)
  - Aapplications specify what to compute not how to compute it in response to each new event.

Streaming Data Processing Design Points

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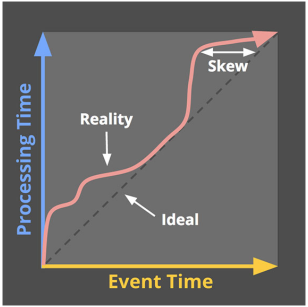
Event Time vs. Processing Time (1/2)

- Event time: the time at which events actually occurred.
    - Timestamps inserted into each record at the source.

- Prcosseing time: the time when the record is received at the streaming application.

Event Time vs. Processing Time (2/2)

- Ideally, event time and processing time should be equal.
- Skew between event time and processing time.



[https://www.oreilly.com/ideas/the-world-beyond-batch-streaming-101]

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  - Time-based policy: based on processing or event time period

Windowing (2/2)

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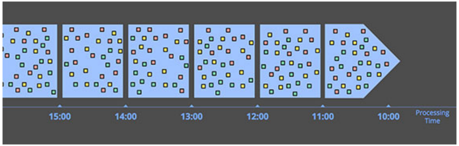
- Tumbling window: supports batch operations.
  - When the buffer fills up, all the tuples are evicted.

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

Windowing by Processing Time

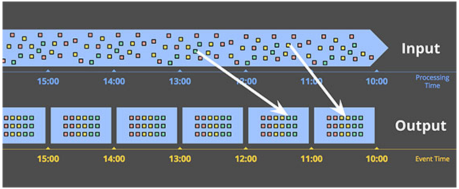
- The system buffers up incoming data into windows until some amount of processing time has passed.
- E.g., five-minute fixed windows



[https://www.oreilly.com/ideas/the-world-beyond-batch-streaming-101]

Windowing by Event Time

- Reflect the times at which events actually happened.
- Handling out-of-order evnets.



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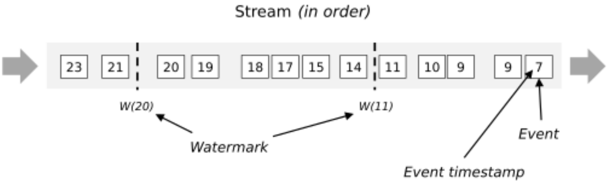
Windowing by Event Time - Watermark (1/2)

- Watermarking helps a stream processing system to deal with lateness.



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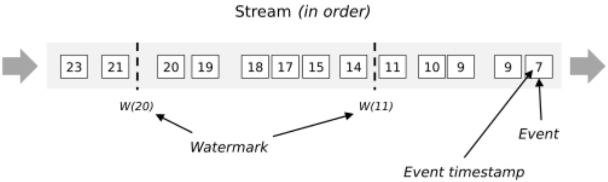

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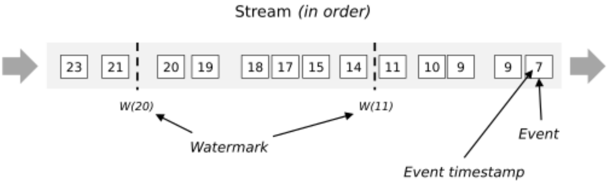

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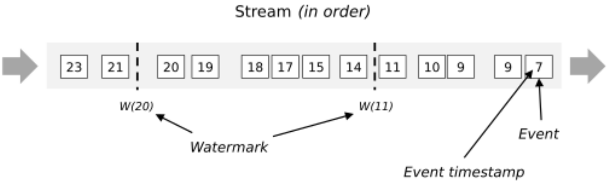
- Streaming systems uses watermarks to measure progress in event time.



Windowing by Event Time - Watermark (2/2)

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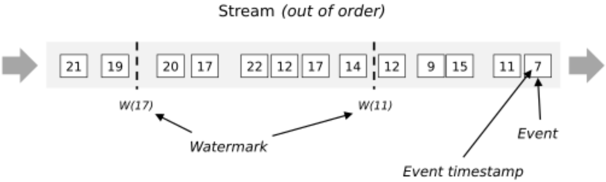
  - There should be no more elements from the stream with a timestamp $t' \leq t$.



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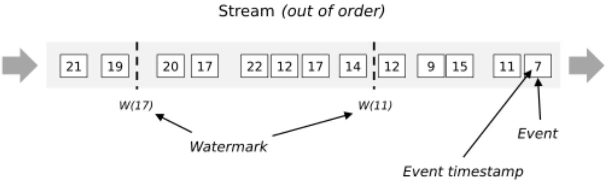

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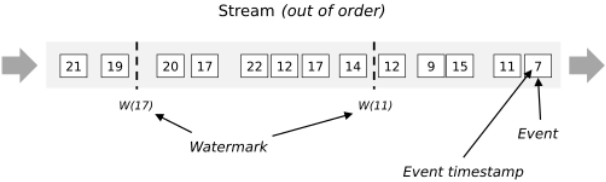

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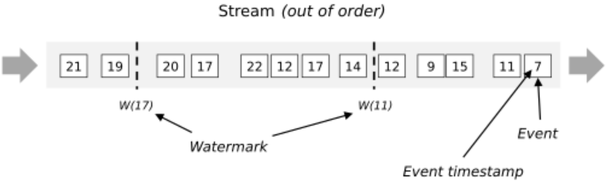
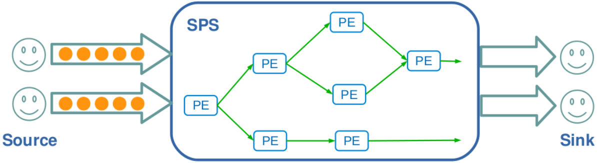
- If an arriving event lies within the watermark, it gets used to update a query.
- Streaming programs may explicitly expect some late elements.



Streaming Data Processing Model

Streaming Data Processing

- 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.



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.
- 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.

PEs States (3/3)

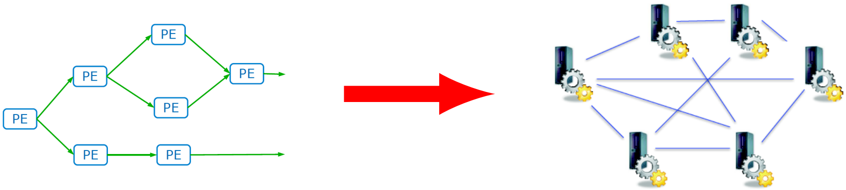
- Stateful tasks: involves maintaining information across different tuples to detect complex patterns.
- A PE is usually a synopsis of the tuples received so far.
- A subset of recent tuples kept in a window buffer.

Job and Job Management

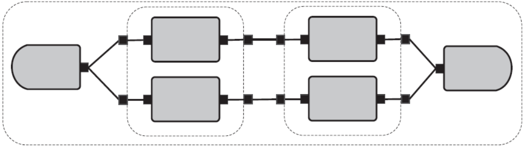
- At runtime, an application is represented by one or more jobs.
- Jobs are deployed as a collection of PEs.
- Job management component must identify and track individual PEs, the jobs they belong to, and associate them with the user that instantiated them.

Logical Plan vs. Physical Plan (1/2)

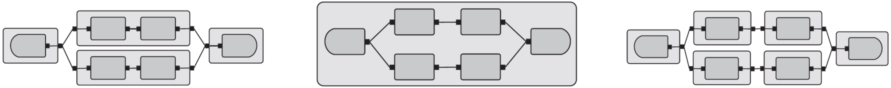
- Logical plan: a data flow graph, where the vertices correspond to PEs, and the edges to stream connections.
- Physical plan: a data flow graph, where the vertices correspond to OS processes, and the edges to transport connections.



Logical Plan vs. Physical Plan (2/2)



Logical plan



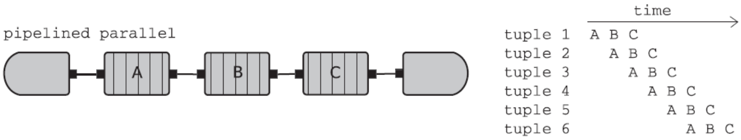
Different physical plans

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

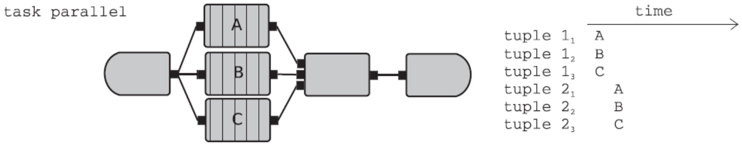
Pipelined Parallelism

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



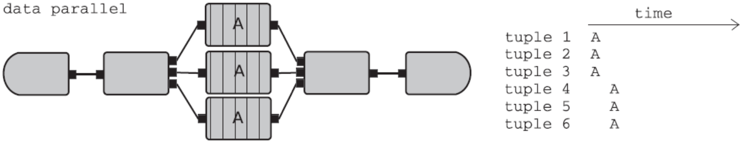
Task Parallelism

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



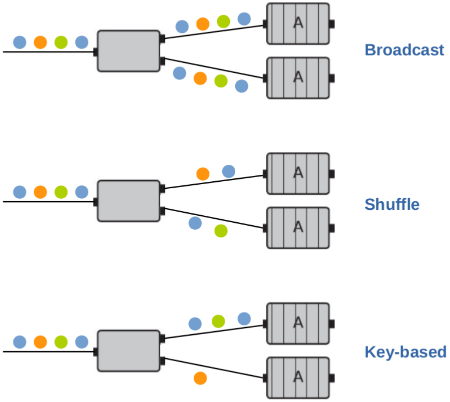
Data Parallelism (1/2)

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



Data Parallelism (2/2)

- How to allocate data items to each computation instance?



Summary

Summary

- Messaging system and partitioned logs
- Decoupling producers and consumers
- Kafka: distributed, topic oriented, partitioned, replicated log service
- Logs, topcs, partition
- Kafka architecture: producer, consumer, broker, coordinator

Summary

- SPS vs. DBMS
- Data stream, unbounded data, tuples
- Event-time vs. processing time
- Micro-batch vs. continues processing (windowing)
- PEs and dataflow
- Stateless vs. Stateful PEs

References

- J. Kreps et al., "Kafka: A distributed messaging system for log processing", NetDB 2011
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- M. Fragkoulis et al., "A Survey on the Evolution of Stream Processing Systems", 2020
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Questions?