POLITECNICO
MILANO 1863

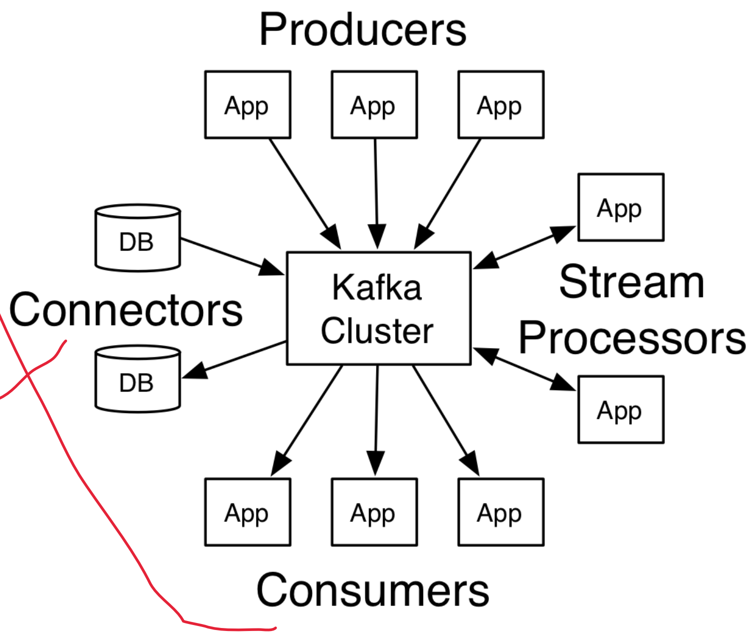
Apache Kafka

Alessandro Margara
alessandro.margara@polimi.it
https://margara.faculty.polimi.it

Apache Kafka: overview

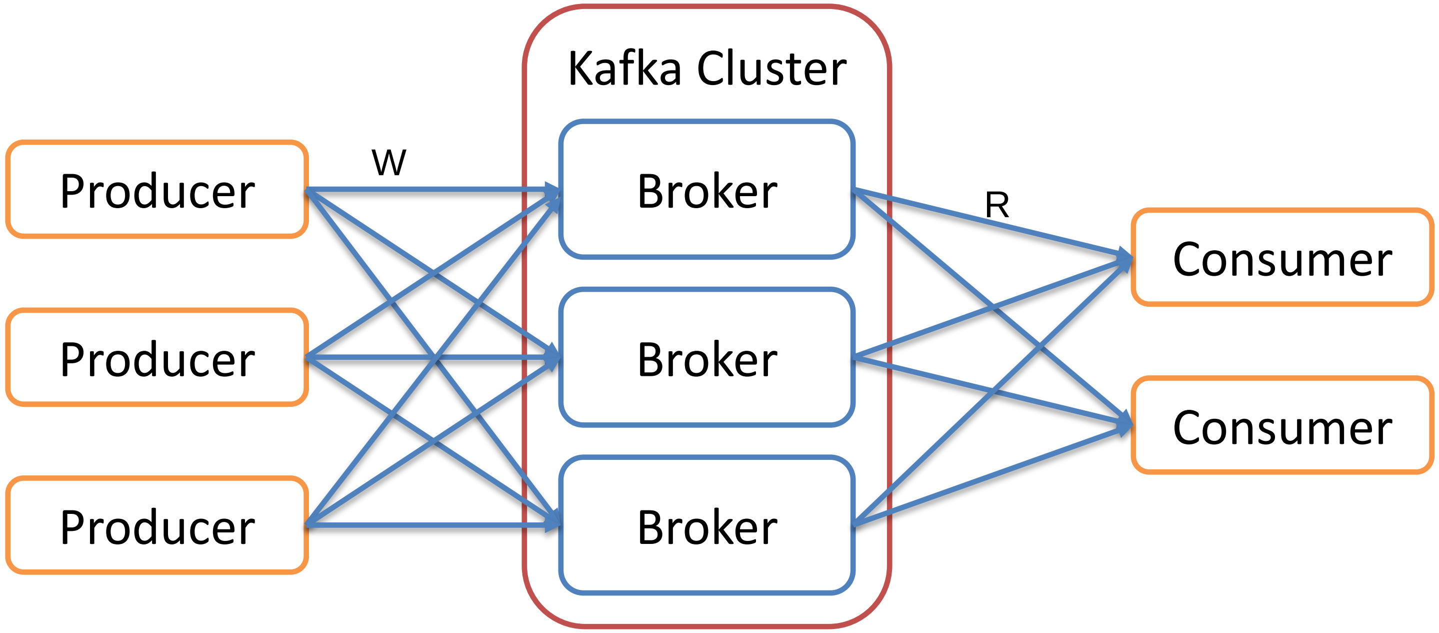
Apache Kafka terminology

- Producer API enables components to write messages to Kafka topics
- Consumer API enables components to read messages from Kafka topics
- Connectors are pre-baked adapters to 3rd party systems
  - Databases that output changes (write log)
  - Sources and sinks of data analytics tools
- More recently, Kafka Streams / KTable API introduced high-level abstractions to develop stream processing applications
  - Consume from one or more input topics
  - Join, aggregate, transform events
  - Write results to one or more output topics



High-level view

- A Kafka cluster consists of multiple servers/brokers
  - Storage and messaging components



Messages

- The basic unit of data in Kafka is a message (or record, or event)
  - Producers write messages to brokers
  - Consumers read messages from brokers

- A message is a key-value pair
  - Keys and values can be any data type
  - All data is stored in Kafka as byte arrays
  - Producers provide serializers to convert the key and value to byte arrays

Communication

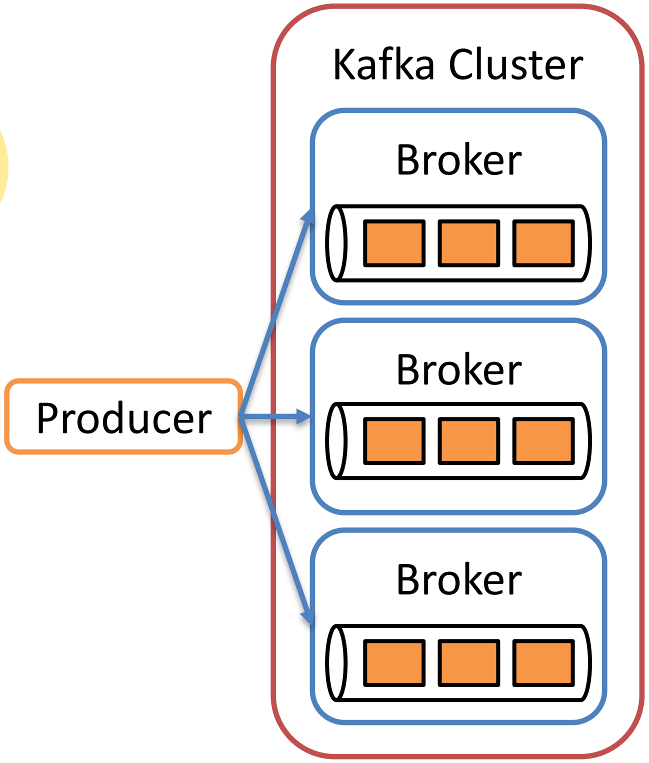
- Communication protocol on top of TCP
- Language-independent
  - Producer and consumer API offered for many languages
- Designed for efficiency

Topics

- Kafka maintains streams of messages called *topics*
- Topics categorize messages into groups
- Developers decide which topics exist
  - By default, a topic is created when it is first used
- One or more producers can write to one or more topics
- There is no limit to the number of topics that can be created

Topics and partitions

- Producers shard data over a set of *partitions*
  - Each partition contains a subset of the topic's messages
  - Each partition is an ordered, immutable log of messages
- Partitions are distributed across brokers



Topics and partitions

- The message key is used to determine which partition a message is assigned to

- Records with the same key are guaranteed to be stored in the same partition

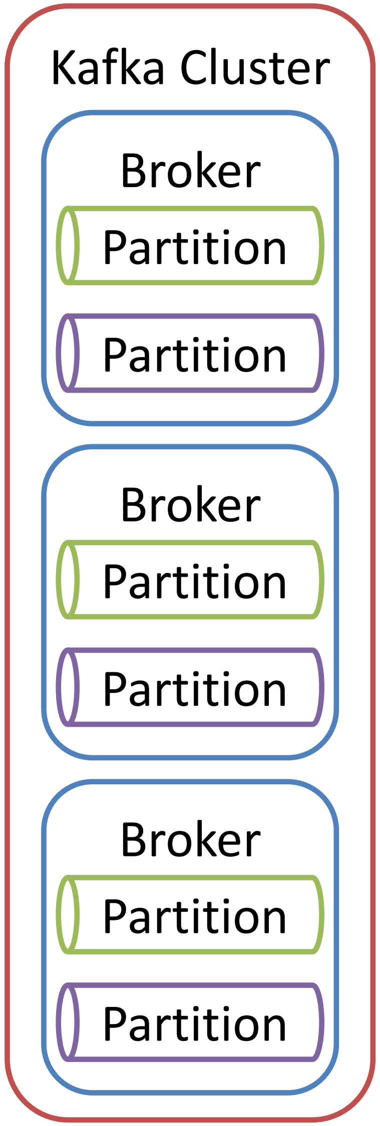
- The partitioning strategy is specified by the producer
  - Default strategy is a hash of the message key
    - Aims to achieve load balance between partitions
  - Developers can provide a custom partitioner class
  - Semantic partitioning: user-specified keys allow locality of data with the same key

Topics

- Kafka stores all messages for a configurable time
  - Both consumed and not consumed messages
- The performance of Kafka is almost constant and independent on the size of the data stored
  - Consequence: storing data for long time is feasible and inexpensive
  - We will see how this is achieved

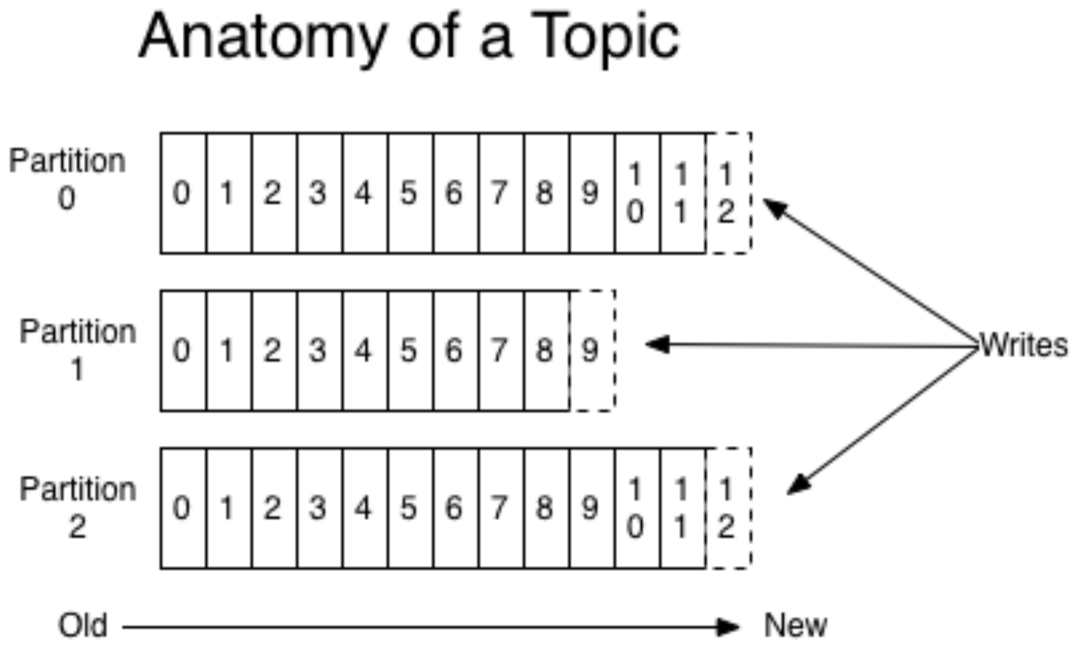
Topics and brokers

- Messages in a topic are spread across partitions in different brokers
  - Typically, a broker manages multiple partitions
- Each partition is stored on the broker's disk as one or more log files
- Each message in the log is identified by its offset number
  - A monotonically increasing value
- Kafka provides a configurable retention policy for messages to manage log file growth
  - Retention policies can be configured per topic



Kafka topic

Every number in partition is an offset and logs continuosly grows monotically



Topics and replication

- Partitions can be replicated across brokers
  - The number of replicas is specified for each topic

- Kafka automatically handles replication
  - Replication only used for fault-tolerance (backup)
  - A leader replica and zero, one or more followers
  - The leader replica handles all requests (both read and write) and propagates changes to the followers

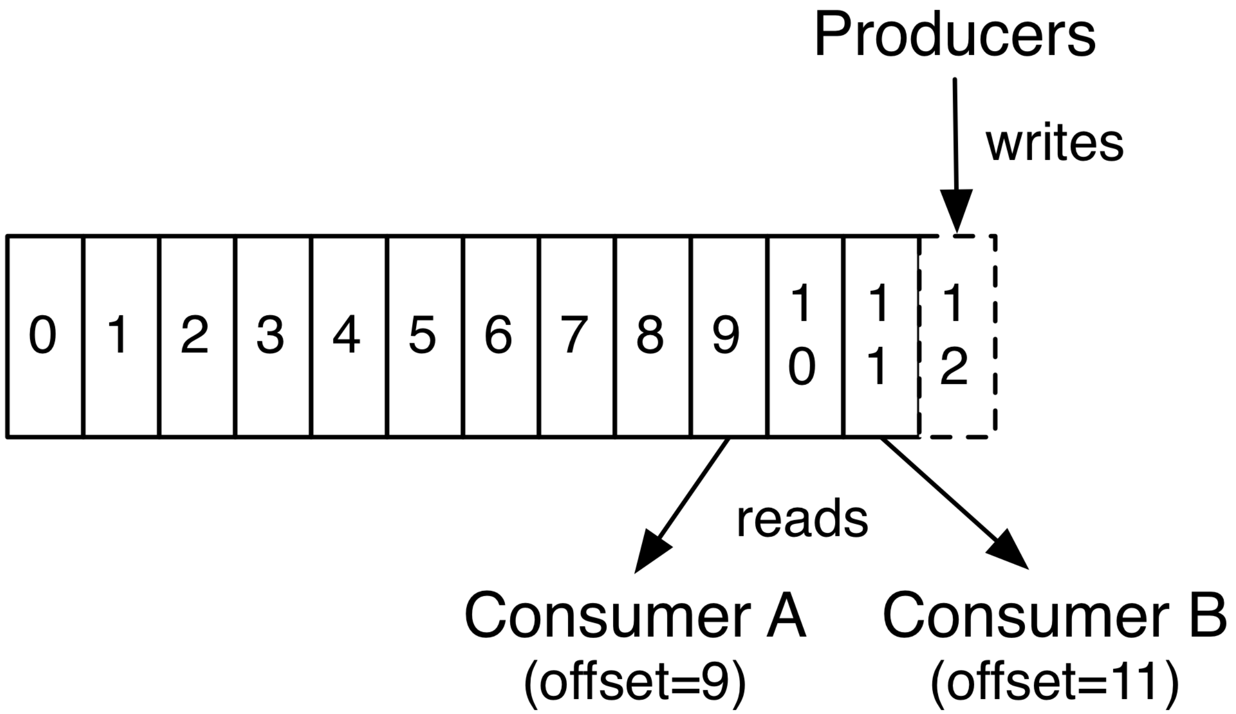
- Replication provides fault-tolerance in case a broker fails
  - A follower takes over in the case the leader fails

Consumers

- Consumers pull messages from one or more topics in the cluster
  - As messages are written to a topic, the consumer will automatically retrieve them

- The *consumer offset* keeps track of the latest message read
  - If necessary, the consumer offset can be changed
    - For example, to re-read old messages
  - It is responsibility of the consumer to store its offset
    - No state management overhead for brokers
    - By default, the consumer offset is also stored in a special Kafka topic

Consumers


Producers
writes
0
1
2
3
4
5
6
7
8
9
10
11
12
reads
Consumer A
(offset=9)
Consumer B
(offset=11)

Consumers

- Different consumers can read data from the same topic
  - By default, each consumer will receive all messages in the topic
  - Easy to add new consumers without impacting on other consumers

- Multiple consumers can be combined into a consumer group
  - Consumer groups provide scaling capabilities
  - Each consumer in a consumer group is assigned a subset of the partitions for consumption

Consumers

- In summary, partitioning of topics serves different purposes
  - Scaling beyond the disk space of a single node
  - Allowing consumers in a consumer group to read in parallel from different partitions
    - Thus, enabling parallel processing of messages
    - Consumers in a consumer group can be different processes, possibly hosted on different machines
    - Limitation: the number of useful consumers in a consumer group is constrained by the number of partitions on the topic

Consumers

- In practice, each consumer group conceptually represents a single logical consumer

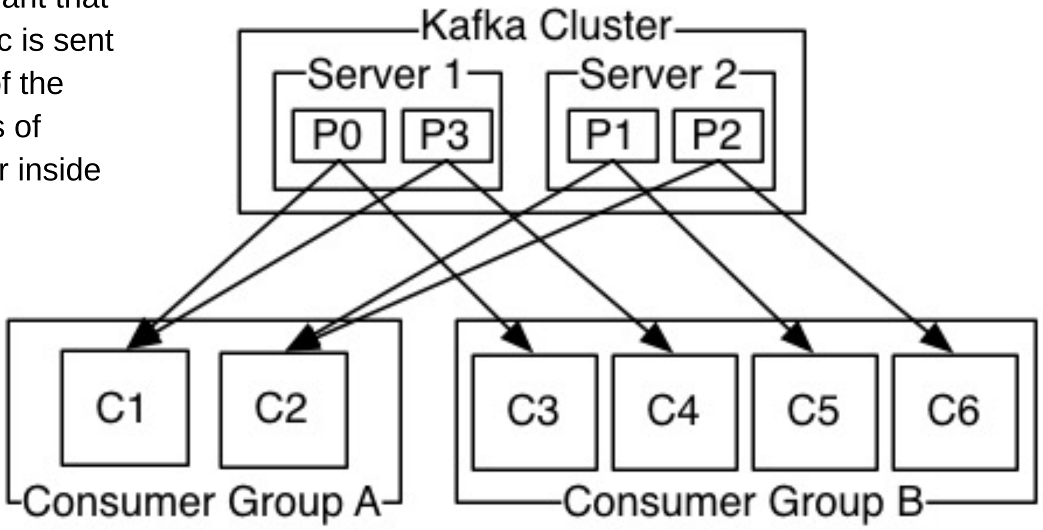
- Each message will be delivered to *each* consumer group interested in the topic

- The message will be delivered to *one* consumer in the consumer group
  - Depending on how the topic is partitioned, …
  - … and how partitions are associated to the consumers within one group

Consumers

- Example
  - Four partitions (P0, P1, P2 , P3)
  - Two consumer groups (A, B)

N.B. Consumer groups represents single applications, so we want that all the messages of the topic is sent to at least one component of the consumer group, regardless of the specific single consumer inside the group



Guarantees

- Kafka offers the following guarantees

1. Messages from a given producer to a given topic partition are added to that partition in FIFO order
2. The offset within a partition reflects the order in which messages are added to that partition
   - Consumers can read in order from each partition
3. Messages with the same key are guaranteed to be stored in the same partition
4. A topic with replication factor N can tolerate the failure of up to N-1 brokers without losing any information

Zookeeper

- Kafka requires well known, standard protocols to manage the cluster of distributed brokers
  - Cluster membership
  - Failure detection and recovery
  - Agreement on available topics and their configuration
  - …
- To do so, it relies on Zookeeper
  - Open-source Apache project
  - Offers an efficient implementation for several widely used protocols for distributed applications (e.g., membership and leader election)
- This motivates why you need to start Zookeeper when running Kafka
  - Recent versions of Kafka are building internal alternatives to implement the same functionalities under the name of KRaft

Design

Why Kafka is different

- Most traditional event-based / message queuing systems
  - Work in main memory
  - Do not persist data at all …
  - … or delete data once it is consumed
- Kafka offers more functionalities
  - Persistency
  - Replay old messages
- Often with better performance
  - Throughput
  - Latency
  - Scalability

Multiple consumers and scalability

- Some traditional queuing systems remove events after they have been read …
- … instead, Kafka persists messages
  - Can be read by multiple consumers

- Multiple brokers, multiple topics, multiple consumers in consumer groups
  - Flexible design that enables distribution and scalability at different levels

Pull architecture

- Kafka consumers pull messages from brokers not broker resposnsability
  - This contrasts with many messaging systems, which use a push-based interaction

- Advantages of pulling
  - Brokers do not store any state for the consumers
    - Consumers are responsible for storing the offset of the last position they have read
    - Add more consumers to the system without reconfiguring the cluster
  - Possibility for a consumer to go offline, resuming from where it left off
  - No problem if the consumer is overloaded
    - The consumer can pull and process the data at the speed it can sustain
    - No effects on the producers or on the cluster

Caching for performance

- Unlike other messaging systems, Kafka does not require a lot of memory
  - Logs are stored on disk and read when required
- Simple data structure: sequential log
  - Unlike most databases, which use tree-based data structure for indexed access
  - Sequential reads are the most efficient operations for disks …
- Kafka takes advantage of the operating system's page cache to hold recently-used data
  - Typically, recently-produced data is the data that consumers are requesting
  - Serving the same data to many consumers becomes less expensive
  - This cache remains warm even if the Kafka server process fails and needs to be restarted!

It leaves more memory to the OS who has better cache resources

Caching for performance

- Kafka does not deserializes / copies the data into the main memory
  - It uses zero-copy data transfer from the page cache to the network

    Fully relies on OS, also for copying data from the network into the disk
- A Kafka broker running on a system with a reasonable amount of RAM for the OS to use as cache will typically provide enough performance to saturate its network connection
  - In practice, the network, not Kafka itself, will be the limiting factor on the speed of the system
- In my opinion, these design choices alone are the key factors the contribute to make Kafka so popular
  - Simple data structure on disk
  - Exploit OS memory optimizations …
  - … and avoid replicating them at the application level