Data-Intensive Distributed Computing
CS 431/631 451/651 (Winter 2021)

Part 9: Real-Time Data Analytics (2/2)

Ali Abedi

These slides are available at https://www.student.cs.uwaterloo.ca/~cs451

This work is licensed under a Creative Commons Attribution-Noncommercial-Share Alike 3.0 United States
See http://creativecommons.org/licenses/by-nc-sa/3.0/us/ for details
Jay Kreps chose to **name** the software after the author Franz **Kafka** because it is "a system optimized for writing", and he liked **Kafka's** work.
Kafka adoption and use cases

- **LinkedIn**: activity streams, operational metrics, data bus
  - 400 nodes, 18k topics, 220B msg/day (peak 3.2M msg/s), May 2014
- **Netflix**: real-time monitoring and event processing
- **Twitter**: as part of their Storm real-time data pipelines
- **Spotify**: log delivery (from 4h down to 10s), Hadoop
- **Loggly**: log collection and processing
- **Mozilla**: telemetry data
- Airbnb, Cisco, Uber, …

https://cwiki.apache.org/confluence/display/KAFKA/Powered+By
How fast is Kafka?

- “Up to 2 million writes/sec on 3 cheap machines”
  - Using 3 producers on 3 different machines, 3x async replication
  - Only 1 producer/machine because NIC already saturated
Why is Kafka so fast?

- Fast **writes**:
  - While Kafka persists all data to disk, essentially all writes go to the **page cache** of OS, i.e. RAM.

- Fast **reads**:
  - Very efficient to transfer data from page cache to a network **socket**
  - Linux: `sendfile()` system call

- Combination of the two = fast Kafka!
  - Example (Operations): On a Kafka cluster where the consumers are mostly caught up you will see no read activity on the disks as they will be serving data entirely from cache.

http://kafka.apache.org/documentation.html#persistence
A first look

• The who is who
  • Producers write data to brokers.
  • Consumers read data from brokers.
  • All this is distributed.

• The data
  • Data is stored in topics.
  • Topics are split into partitions, which are replicated.
A first look

http://www.michael-noll.com/blog/2013/03/13/running-a-multi-broker-apache-kafka-cluster-on-a-single-node/
Topics

- **Topic**: feed name to which messages are published
  - Example: “zerg.hydra”

*Kafka prunes “head” based on age or max size or “key”*

Producers always append to “tail” (think: append to a file)
Topics

Producers always append to "tail" (think: append to a file)

Producers use an "offset pointer" to track/control their read progress (and decide the pace of consumption)

Consumers use an "offset pointer" to track/control their read progress (and decide the pace of consumption)

Older msgs  Newer msgs

Consumer group C1
Consumer group C2
Producer A1
Producer A2
Producer An

Broker(s)
Partitions

- A topic consists of **partitions**.
- Partition: **ordered + immutable** sequence of messages that is continually appended to

**Anatomy of a Topic**

<table>
<thead>
<tr>
<th>Partition 0</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>1</th>
<th>1</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partition 1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partition 2</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Old** ➔ **New**

Writes
Partitions

• #partitions of a topic is configurable
• #partitions determines **max** consumer (group) parallelism

- Consumer group A, with 2 consumers, reads from a 4-partition topic
- Consumer group B, with 4 consumers, reads from the same topic
Partition offsets

- **Offset**: messages in the partitions are each assigned a unique (per partition) and sequential id called the *offset*
  - Consumers track their pointers via \((offset, partition, topic)\) tuples
Replicas of a partition

• Replicas: “backups” of a partition
  • They exist solely to prevent data loss.
  • Replicas are never read from, never written to.
    • They do NOT help to increase producer or consumer parallelism!
• Kafka tolerates \((numReplicas - 1)\) dead brokers before losing data
  • LinkedIn: numReplicas == 2 → 1 broker can die
Topics vs. Partitions vs. Replicas

A topic configured to use 4 partitions.

Each partition has an ID.

The ID of a replica is the same as the ID of the broker that hosts it.

For each partition, Kafka will elect one broker as the “leader”.

If, say, the replication factor of a topic is set to 3, then Kafka will create 3 identical replicas of each partition and place those replicas on available brokers in the cluster.

http://www.michael-noll.com/blog/2013/03/13/running-a-multi-broker-apache-kafka-cluster-on-a-single-node/
probabilistic data structures for Big data and streaming
Streams Processing Challenges

Inherent challenges
- Latency requirements
- Space bounds

System challenges
- Bursty behavior and load balancing
- Out-of-order message delivery and non-determinism
- Consistency semantics (at most once, exactly once, at least once)
Algorithmic Solutions

Throw away data
   Sampling

Accepting some approximations
   Hashing
Reservoir Sampling

Task: select $s$ elements from a stream of size $N$ with uniform probability

$N$ can be very very large
We might not even know what $N$ is! (infinite stream)

Solution: Reservoir sampling

Store first $s$ elements
For the $k$-th element thereafter, keep with probability $s/k$
(randomly discard an existing element)

Example: $s = 10$

Keep first 10 elements
11th element: keep with 10/11
12th element: keep with 10/12
...

Reservoir Sampling: How does it work?

Example: $s = 10$
- Keep first 10 elements
- 11th element: keep with $10/11$

If we decide to keep it: sampled uniformly by definition
- Probability existing item is discarded: $10/11 \times 1/10 = 1/11$
- Probability existing item survives: $10/11$

General case: at the $(k + 1)\text{th}$ element
- Probability of selecting each item up until now is $s/k$
- Probability existing item is discarded: $s/(k+1) \times 1/s = 1/(k + 1)$
- Probability existing item survives: $k/(k + 1)$
- Probability each item survives to $(k + 1)\text{th}$ round:
  $(s/k) \times k/(k + 1) = s/(k + 1)$
Hashing for Three Common Tasks

Cardinality estimation
What’s the cardinality of set $S$?
How many unique visitors to this page?
HashSet  HLL counter

Set membership
Is $x$ a member of set $S$?
Has this user seen this ad before?
HashSet  Bloom Filter

Frequency estimation
How many times have we observed $x$?
How many queries has this user issued?
HashMap  CMS
HyperLogLog Counter

Task: cardinality estimation of set
\[ \text{size()} \rightarrow \text{number of unique elements in the set} \]

Observation: hash each item and examine the hash code
- On expectation, 1/2 of the hash codes will start with 0
- On expectation, 1/4 of the hash codes will start with 00
- On expectation, 1/8 of the hash codes will start with 000
- On expectation, 1/16 of the hash codes will start with 0000
  ...

How do we take advantage of this observation?
Bloom Filters

Task: keep track of set membership
- \( \text{put}(x) \rightarrow \text{insert } x \text{ into the set} \)
- \( \text{contains}(x) \rightarrow \text{yes if } x \text{ is a member of the set} \)

Components
- \( m \)-bit bit vector
- \( k \) hash functions: \( h_1, \ldots, h_k \)

\[ \begin{array}{cccccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array} \]
Bloom Filters: put

\[ h_1(x) = 2 \]
\[ h_2(x) = 5 \]
\[ h_3(x) = 11 \]
Bloom Filters: put

put $\times$

0 1 0 0 1 1 0 0 0 0 0 1 1 0
Bloom Filters: contains $x$ such that:

- $h_1(x) = 2$
- $h_2(x) = 5$
- $h_3(x) = 11$
Bloom Filters: contains

contains $x$

$h_1(x) = 2$
$h_2(x) = 5$
$h_3(x) = 11$

AND $\{A[h_1(x)], A[h_2(x)], A[h_3(x)]\} = \text{YES}$
Bloom Filters: contains

contains \( y \)

\[ h_1(y) = 2 \]
\[ h_2(y) = 6 \]
\[ h_3(y) = 9 \]
contains $y$

$h_1(y) = 2$
$h_2(y) = 6$
$h_3(y) = 9$

AND $\left\{ A[h_1(y)] \right\} = NO$

What’s going on here?
Bloom Filters

Error properties: contains(x)
   False positives possible
   No false negatives

Usage
   Constraints: capacity, error probability
   Tunable parameters: size of bit vector $m$, number of hash functions $k$
Count-Min Sketches

Task: frequency estimation

- put($x$) → increment count of $x$ by one
- get($x$) → returns the frequency of $x$

Components

- $m$ by $k$ array of counters
- $k$ hash functions: $h_1, \ldots, h_k$
Count-Min Sketches: put

\[ h_1(x) = 2 \]
\[ h_2(x) = 5 \]
\[ h_3(x) = 11 \]
\[ h_4(x) = 4 \]
Count-Min Sketches: put

put \(x\)

\[
\begin{array}{ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
\end{array}
\]
Count-Min Sketches: put

- $h_1(x) = 2$
- $h_2(x) = 5$
- $h_3(x) = 11$
- $h_4(x) = 4$

```
0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0
```
Count-Min Sketches: put

put ✗

Count-Min Sketches: put

<table>
<thead>
<tr>
<th>0</th>
<th>2</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

35
Count-Min Sketches: put

- \( h_1(y) = 6 \)
- \( h_2(y) = 5 \)
- \( h_3(y) = 12 \)
- \( h_4(y) = 2 \)

The diagram shows the process of putting an element into a Count-Min Sketch. The values for each hash function are as follows:

- For \( h_1(y) \), the sketch is incremented by 6.
- For \( h_2(y) \), the sketch is incremented by 5.
- For \( h_3(y) \), the sketch is incremented by 12.
- For \( h_4(y) \), the sketch is incremented by 2.
Count-Min Sketches: put

<p>| | | | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

37
Count-Min Sketches: get

$h_1(x) = 2$
$h_2(x) = 5$
$h_3(x) = 11$
$h_4(x) = 4$

get $x$
get $x$  

$\begin{align*}
h_1(x) &= 2 \\
h_2(x) &= 5 \\
h_3(x) &= 11 \\
h_4(x) &= 4
\end{align*}$

$$A[h_1(x)] \quad A[h_2(x)] \quad A[h_3(x)] \quad A[h_4(x)]$$

MIN $= 2$

Count-Min Sketches: get
Count-Min Sketches: get

\[ h_1(y) = 6 \]
\[ h_2(y) = 5 \]
\[ h_3(y) = 12 \]
\[ h_4(y) = 2 \]
Count-Min Sketches: get

\[ h_1(y) = 6 \]
\[ h_2(y) = 5 \]
\[ h_3(y) = 12 \]
\[ h_4(y) = 2 \]

\[ \{ A[h_1(y)] \} = 1 \]

Count-Min Sketches: get

\[ A[h_1(y)] \]
\[ A[h_2(y)] \]
\[ A[h_3(y)] \]
\[ A[h_4(y)] \]
Count-Min Sketches

Error properties: \( \text{get}(x) \)
Reasonable estimation of heavy-hitters
Frequent over-estimation of tail

Usage
Constraints: number of distinct events, distribution of events, error bounds
Tunable parameters: number of counters \( m \) and hash functions \( k \), size of counters
Hashing for Three Common Tasks

Cardinality estimation
What’s the cardinality of set $S$?
How many unique visitors to this page?
HashSet  HLL counter

Set membership
Is $x$ a member of set $S$?
Has this user seen this ad before?
HashSet  Bloom Filter

Frequency estimation
How many times have we observed $x$?
How many queries has this user issued?
HashMap  CMS
More information on Kafka (optional reading)
Writing data to Kafka
Writing data to Kafka

• You use Kafka “producers” to write data to Kafka brokers.
  • Available for JVM (Java, Scala), C/C++, Python, Ruby, etc.

• A simple example producer:

```java
Properties props = new Properties();
props.put("metadata.broker.list", "...");
ProducerConfig config = new ProducerConfig(props);
Producer p = new Producer(ProducerConfig config);
KeyedMessage<K, V> msg = ...; // cf. later slides
p.send(KeyedMessage<K,V> message);
```
Producers

- Two types of producers: “async” and “sync”

```java
Properties props = new Properties();
props.put("producer.type", "async");
ProducerConfig config = new ProducerConfig(props);
```

- Same API and configuration, but slightly different semantics.
- What applies to a sync producer almost always applies to async, too.
- Async producer is preferred when you want higher throughput.
Producers

- Two aspects worth mentioning because they significantly influence Kafka performance:
  1. Message acking
  2. Batching of messages
1) Message acking

- Background:
  - In Kafka, a message is considered *committed* when “any required” replica for that partition have applied it to their data log.
  - Message acking is about conveying this “Yes, committed!” information back from the brokers to the producer client.
  - Exact meaning of “any required” is defined by request.required.acks.

- Only **producers** must configure acking
  - Exact behavior is configured via request.required.acks, which determines when a produce request is considered completed.
  - Allows you to trade **latency (speed) <=> durability (data safety)**.
  - Consumers: Acking and how you configured it on the side of producers do not matter to consumers because only committed messages are ever given out to consumers. They don’t need to worry about potentially seeing a message that could be lost if the leader fails.
1) Message acking

- Typical values of `request.required.acks`
  - 0: producer never waits for an ack from the broker.
    - Gives the lowest latency but the weakest durability guarantees.
  - 1: producer gets an ack after the leader replica has received the data.
    - Gives better durability as we wait until the lead broker acks the request. Only msgs that were written to the now-dead leader but not yet replicated will be lost.
  - -1: producer gets an ack after all replicas have received the data.
    - Gives the best durability as Kafka guarantees that no data will be lost as long as at least one replica remains.
2) Batching of messages

- Batching improves throughput
  - Tradeoff is data loss if client dies before pending messages have been sent.

- You have two options to “batch” messages:
  1. Use `send(listOfMessages)`.

```java
producer.send(List<KeyedMessage<K, V>> messages);
```
  - Sync producer: will send this list (“batch”) of messages *right now*. Blocks!
  - Async producer: will send this list of messages in background “as usual”, i.e. according to batch-related configuration settings. Does not block!

  2. Use `send(singleMessage)` with async producer.

```java
producer.send(KeyedMessage<K, V> message);
```
  - For async the behavior is the same as `send(listOfMessages)`.
Reading data from Kafka
Reading data from Kafka

- You use Kafka “consumers” to write data to Kafka brokers.
  - Available for JVM (Java, Scala), C/C++, Python, Ruby, etc.
Reading data from Kafka

- Consumers *pull* from Kafka (there’s no push)
  - Allows consumers to control their pace of consumption.
  - Allows to design downstream apps for *average* load, not peak load

- Consumers are responsible to track their read positions aka “offsets”
Reading data from Kafka

- Consumer “groups”
  - Allows multi-threaded and/or multi-machine consumption from Kafka topics.
  - Consumers “join” a group by using the same group.id
  - Kafka guarantees a message is only ever read by a single consumer in a group.
    - Kafka assigns the partitions of a topic to the consumers in a group so that each partition is consumed by exactly one consumer in the group.
    - Maximum parallelism of a consumer group: \( \#\text{consumers} \) (in the group) \( \leq \#\text{partitions} \)
Guarantees when reading data from Kafka

• A message is only ever read by a single consumer in a group.
• A consumer sees messages in the order they were stored in the log.
• The order of messages is only guaranteed within a partition.
Rebalancing: how consumers meet brokers

- The assignment of brokers – via the partitions of a topic – to consumers is quite **important**, and it is **dynamic** at run-time.