

Chapter 16: Partitioning

1. What is Partitioning and Why is it Needed?

- **Definition:** When an application’s data volume grows too large to fit on a single machine, it needs to be split into smaller pieces called **partitions** or **shards**. Each partition is small enough to fit on an individual node.
- **Primary Goal:** To manage *large datasets* that exceed the capacity of a single machine.
- **Additional Benefit:** Increases the system’s capacity for handling requests because the *load of accessing data is spread* across multiple nodes.

2. The Role of a Gateway Service

- When a client sends a request to a partitioned system, it needs to be routed to the *correct node(s)*.
- A **gateway service** (like a reverse proxy) is typically responsible for this routing.
- The gateway knows how data is mapped to partitions and nodes.
- This data-to-partition mapping is usually maintained by a *fault-tolerant coordination service* (e.g., etcd or Zookeeper).
A partitioned application with a gateway that routes requests to partitions

3. Complexities and Drawbacks of Partitioning

Partitioning is not without its challenges and introduces significant complexity:

- **Gateway Requirement:** A gateway service is *necessary* to direct requests to the appropriate nodes.
- **Data Aggregation:** To roll up data across different partitions (e.g., for a “group by” operation), data must be fetched from multiple partitions and then aggregated, which *adds complexity*.
- **Cross-Partition Transactions:** Transactions that need to atomically update data spanning multiple partitions *limit scalability*.
- **Hotspots:** If certain partitions are accessed much more frequently than others (becoming “*hotspots*”), the system’s ability to scale is constrained.
- **Dynamic Resizing (Rebalancing):** Adding or removing partitions at runtime is *challenging* because it requires moving data across nodes.

4. Partitioning and Caches

- Caches are *well-suited* for partitioning because they avoid many of the common complexities.
- For instance, caches generally *don’t require atomic updates* across partitions or complex aggregations spanning multiple partitions.

5. Prerequisite for Key Partitioning

- A fundamental requirement for partitioning key-value data is that the number of possible keys must be *very large*.
- Keys with a small set of possible values (e.g., a boolean key with only two values) are *not suitable* for partitioning as they allow for a very limited number of partitions.

6. Methods of Mapping Key-Value Data to Partitions

There are two primary ways to map key-value pairs to partitions:

6.1. Range Partitioning

- **Definition:** Splits data by *key range* into lexicographically sorted partitions (e.g., A-H, I-P, Q-Z).
A range-partitioned dataset
- **Performance:** Each partition is generally stored in *sorted order on disk* to make range scans fast.
- **Challenges:**
 - **Picking Boundaries:**
 - * Evenly splitting the key range works well if key distribution is *uniform*.
 - * If not uniform (like words in a dictionary), partitions can become *unbalanced*, with some having significantly more entries.
 - **Hotspots:** Certain access patterns can lead to hotspots. For example, if data is range-partitioned by date, all requests for the current day might hit a *single node*.
 - * Workaround: Adding a random prefix to partition keys (adds complexity).
- **Rebalancing (Adding/Removing Nodes):**
 - **Need:** When data size or request volume changes, nodes need to be added or removed to balance the load and manage costs. This process is called **rebalancing**.
 - **Goal:** Rebalancing should *minimize system disruption* and the amount of data transferred.
 - **Static Partitioning:**
 - * Create *many more partitions* than initially needed and assign multiple partitions to each node. The number of partitions remains fixed.
 - * When a new node is added, some partitions are moved from existing nodes to the new one to maintain balance.
 - * **Drawbacks:**
 - The number of partitions is *fixed* and hard to change.
 - Getting the initial number of partitions right is difficult: too many can add overhead and decrease performance; too few can limit scalability.

- Some partitions might still become hotspots.
- **Dynamic Partitioning:**
 - * Partitions are created *on demand*.
 - * The system starts with a single partition. When it grows too large or becomes too hot, it's split into two sub-partitions (approximately half the data each), and one sub-partition is moved to a new node.
 - * Conversely, if two adjacent partitions become small or “cold” enough, they can be merged.

6.2. Hash Partitioning

- **Definition:** Uses a *hash function* to deterministically map a key to a seemingly random number (a hash) within a defined range (e.g., 0 to $2^{64} - 1$). This ensures keys' hashes are distributed *uniformly* across the range.
 - A subset of these hashes is then assigned to each partition.
 - Example: $\text{hash}(\text{key}) \bmod N$, where N is the number of partitions.
A hash-partitioned dataset
- **Benefit:** Generally ensures partitions contain a *relatively similar number of entries*.
- **Challenges:**
 - **Hotspots:** Does *not eliminate hotspots* if the access pattern is non-uniform. If a single key is accessed very frequently, the node hosting its partition can become overloaded.
 - * Solutions: Further split the hot partition (increasing N) or split the hot key into sub-keys (e.g., by prepending a random prefix).
 - **Rebalancing with Modulo Operator:** When a new partition is added using the $\text{hash}(\text{key}) \bmod N$ approach, *most keys have to be moved* (shuffled) to different partitions because their assignment changes. This shuffling is very expensive due to network bandwidth and resource consumption.
 - * Ideally, adding a partition should only require shuffling K/N keys (where K is total keys, N is number of partitions).
- **Consistent Hashing:**
 - A widely used hashing strategy that *minimizes data shuffling* during rebalancing.
 - **How it works:** - A hash function randomly maps both partition identifiers and keys onto an *imaginary circle*. - Each key is assigned to the *closest partition* that appears on the circle in a clockwise direction. With consistent hashing, partition identifiers and keys are randomly distributed around a circle, and each key is assigned to the next partition that appears on the circle in clockwise order

- **Adding a new partition:** When a new partition is added to the circle, *only the keys that now map to this new partition* (due to proximity on the circle) need to be reassigned. Other key assignments remain unchanged.
After partition P4 is added, the key 'for' is reassigned to P4, but the assignment of the other keys doesn't change
- **Main Drawback of Hash Partitioning (vs. Range Partitioning):**
 - The *sort order of keys across partitions is lost*. This makes efficiently scanning all data in order difficult.
 - However, data *within* an individual partition can still be sorted based on a secondary key.