COEN6731 Distributed Software Systems

Week 7: Consistent Hashing and CAP

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Today's outline

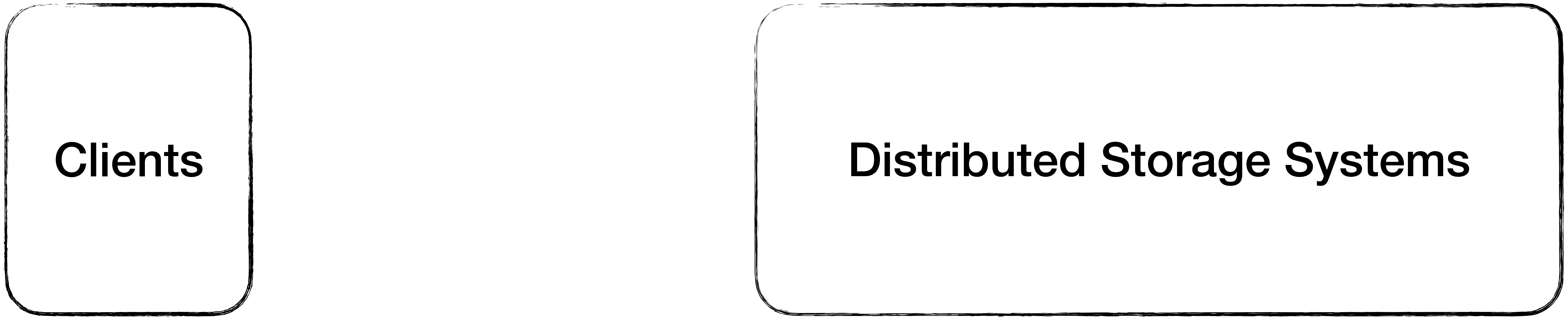
Consistent Hashing

CAP

Let’s build a distributed storage system

We aim to build a **distributed key–value storage** service that:

- Stores a large number of key–value pairs (data) across multiple servers
- Servers collectively provide a scalable distributed storage service
- Supports at least two basic operations: PUT (store) and GET (retrieve)



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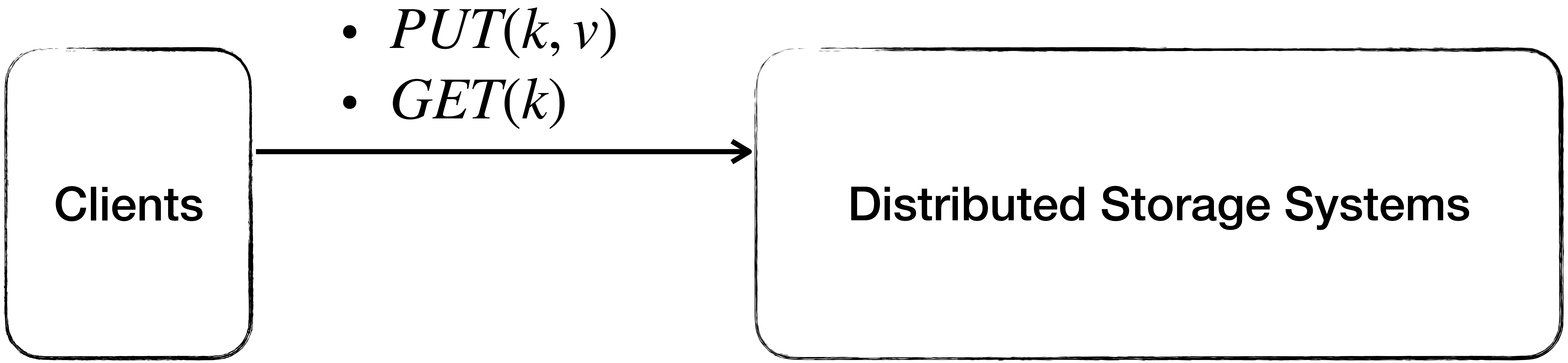

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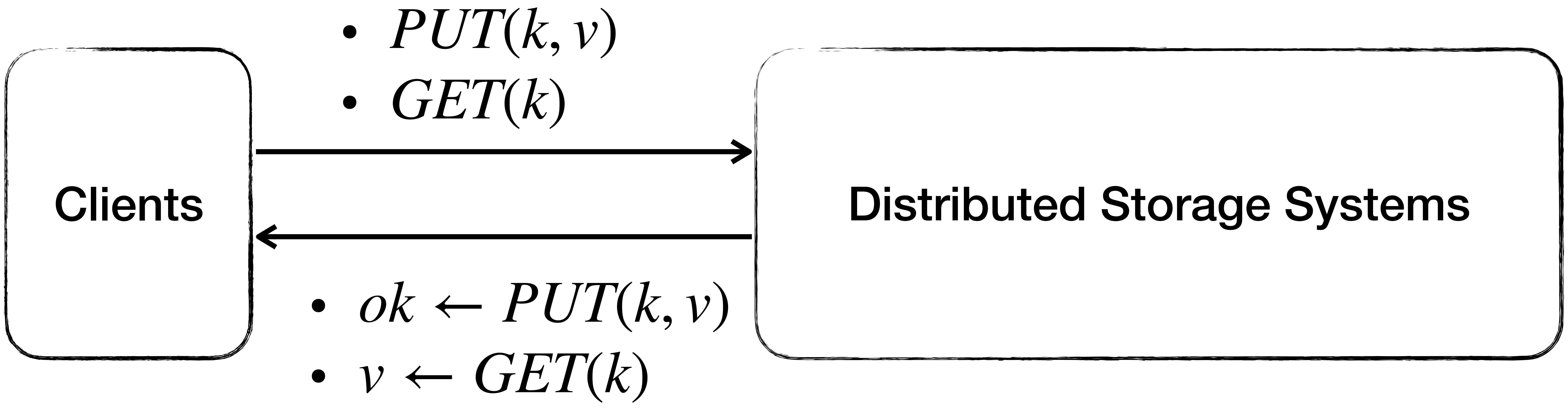

Naive Hashing

- Let’s try the simple solution:
  - server = hash(key) % N
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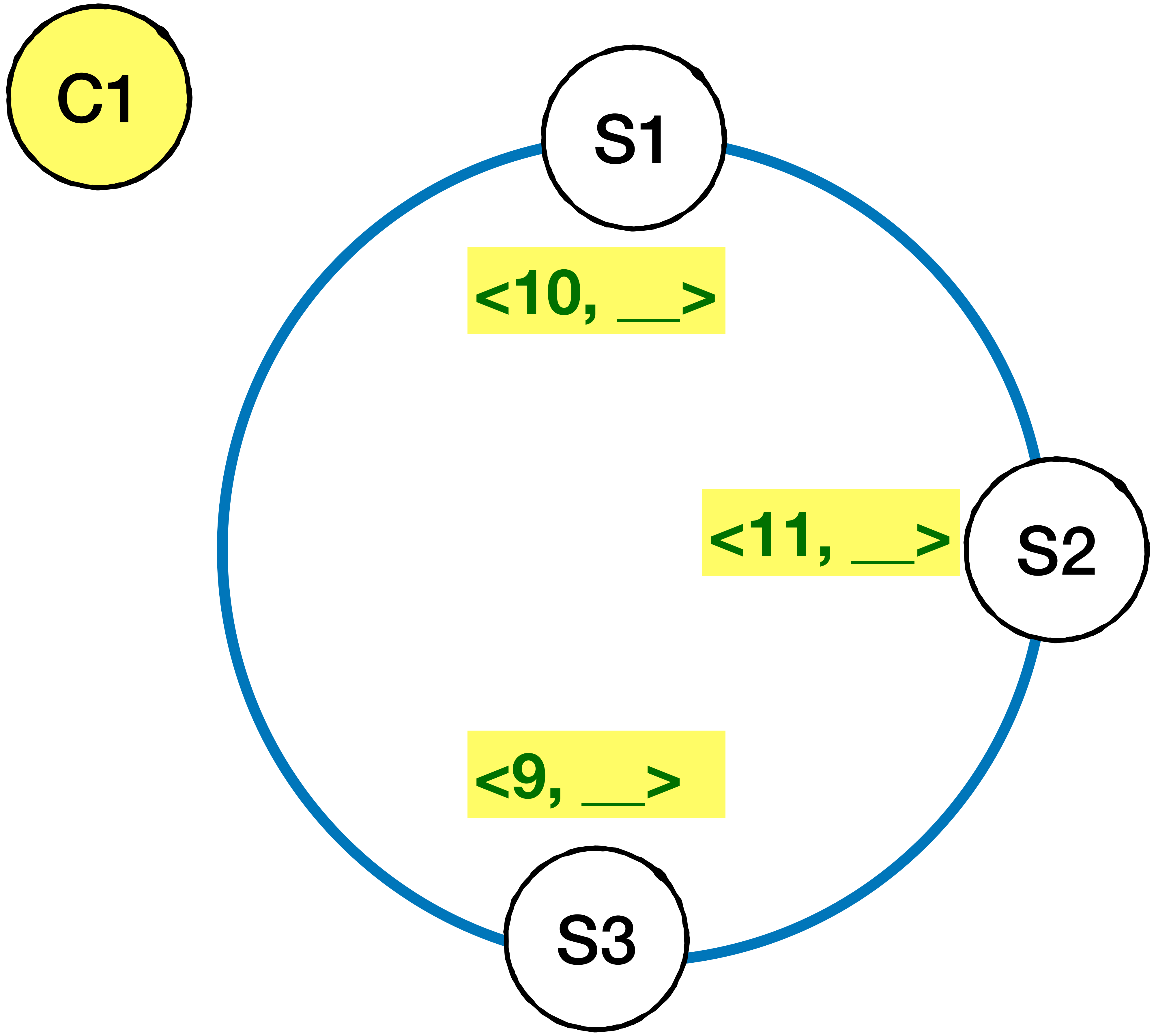

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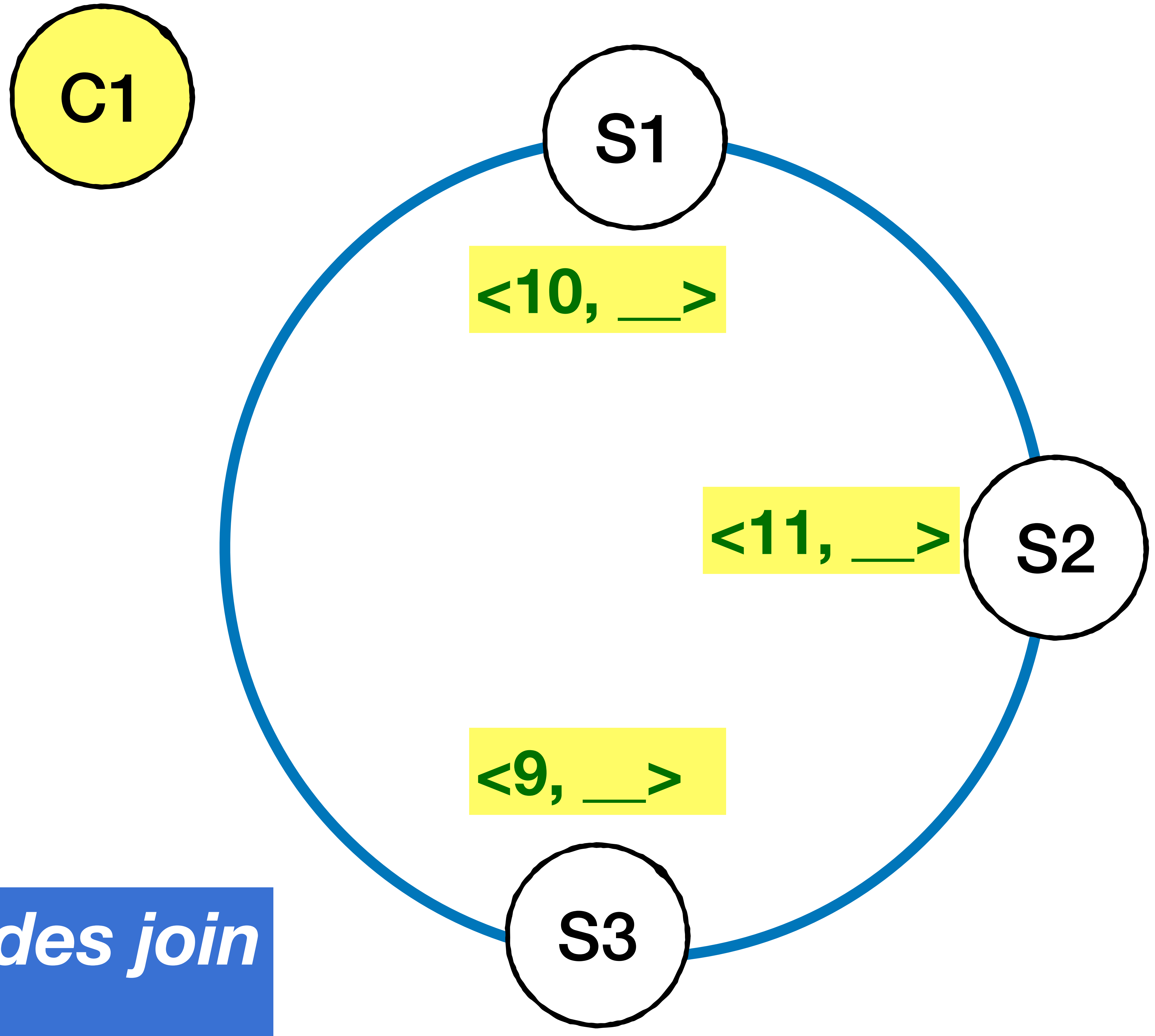

What happens when nodes join or leave?

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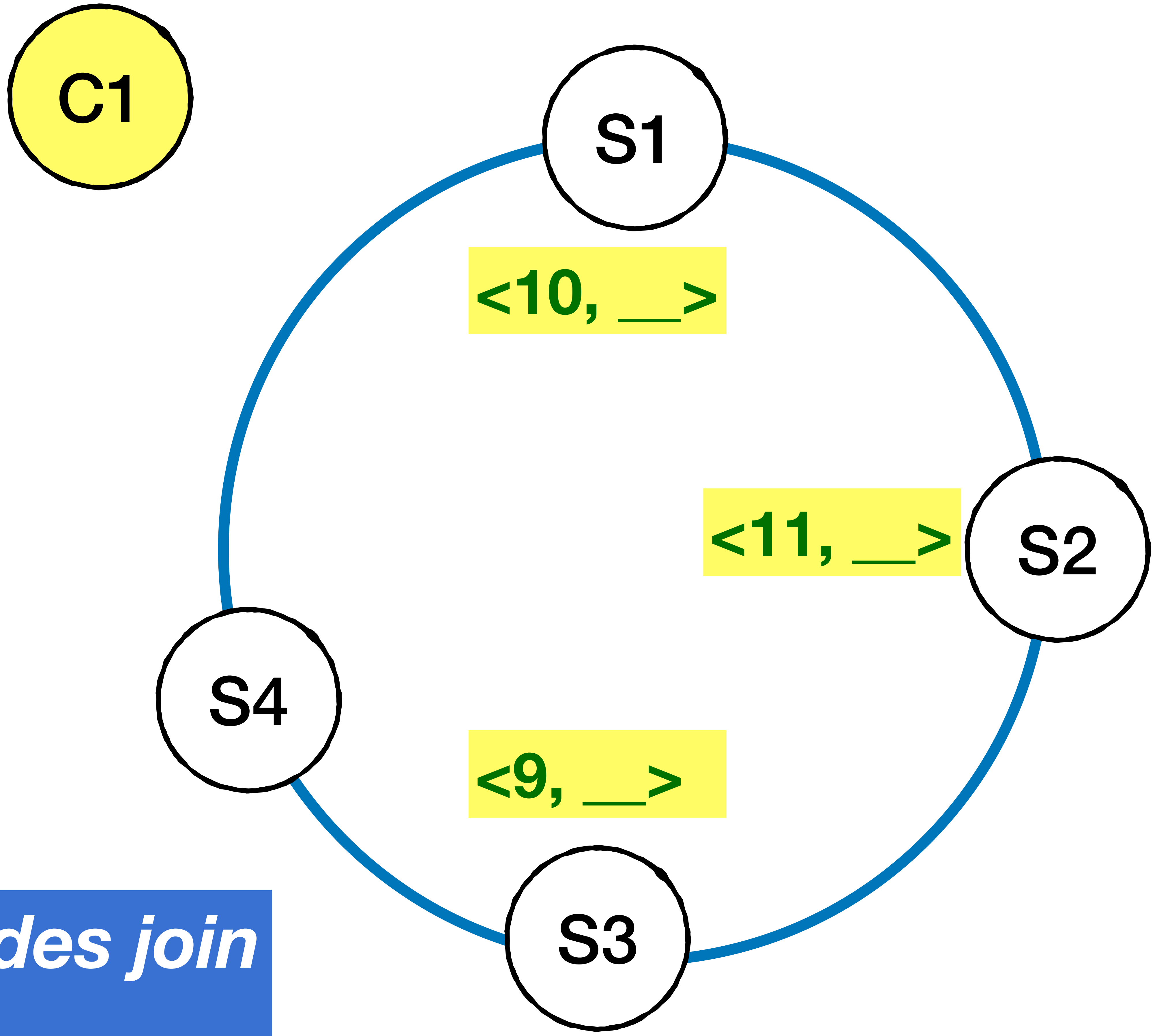

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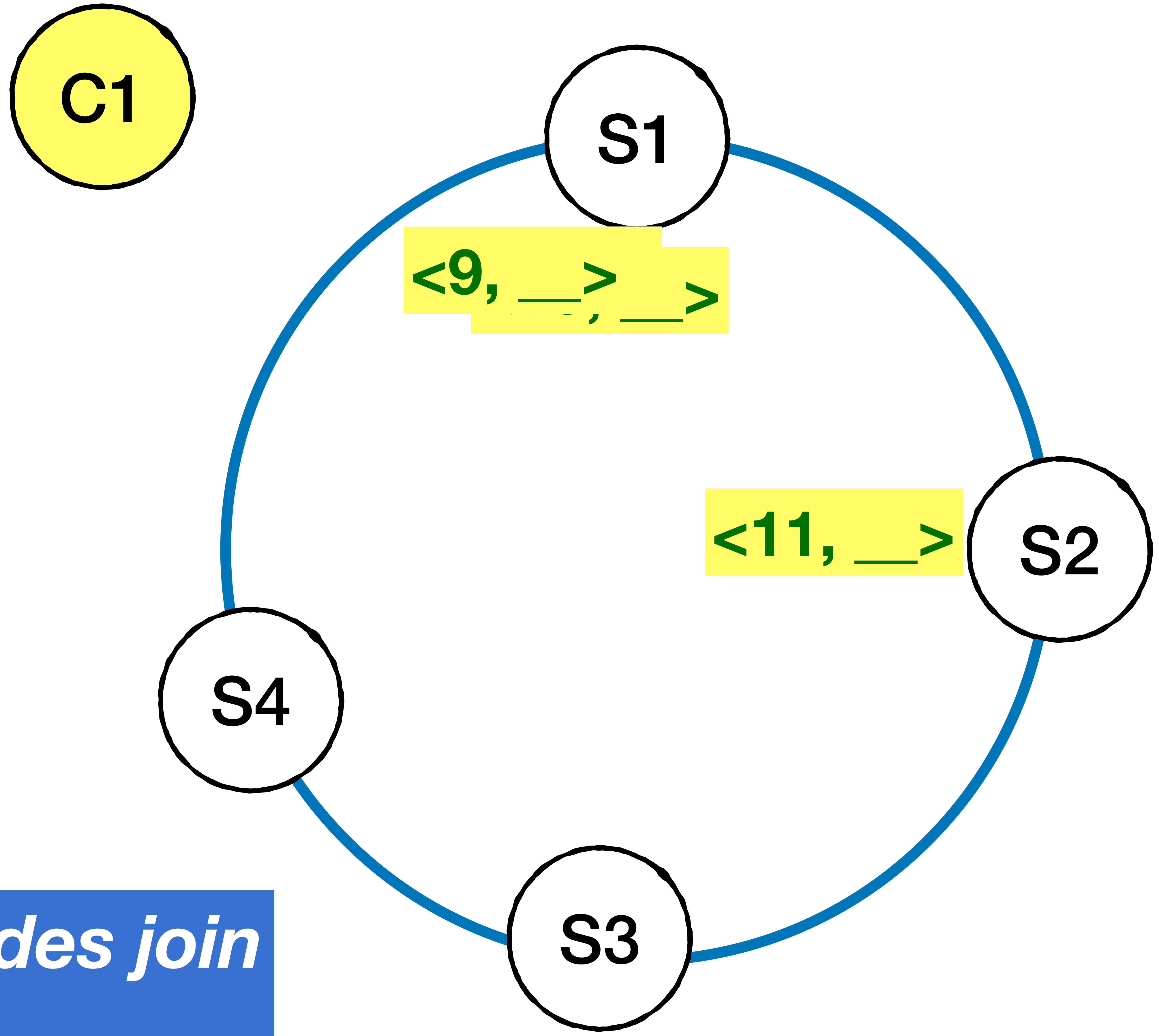

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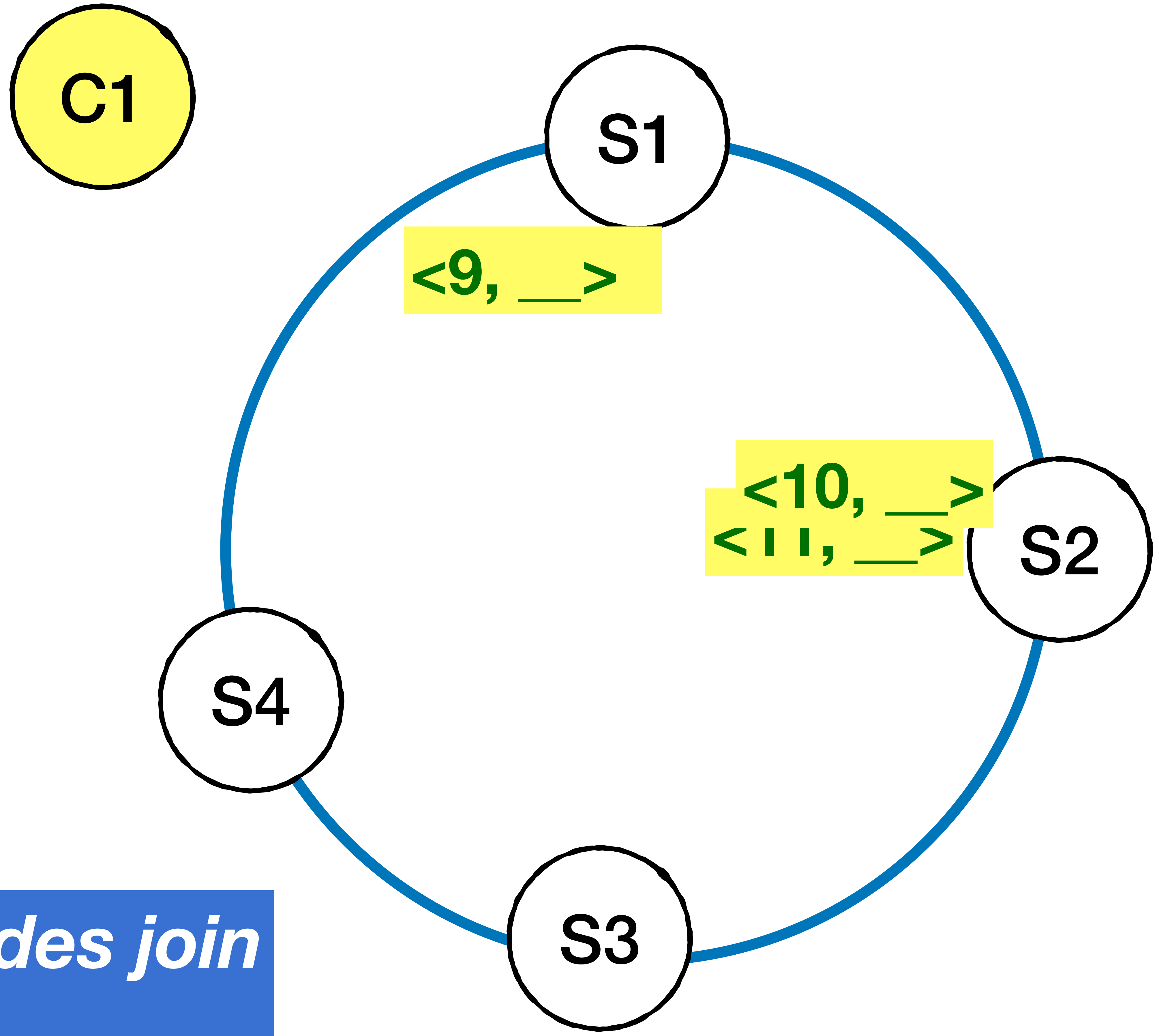

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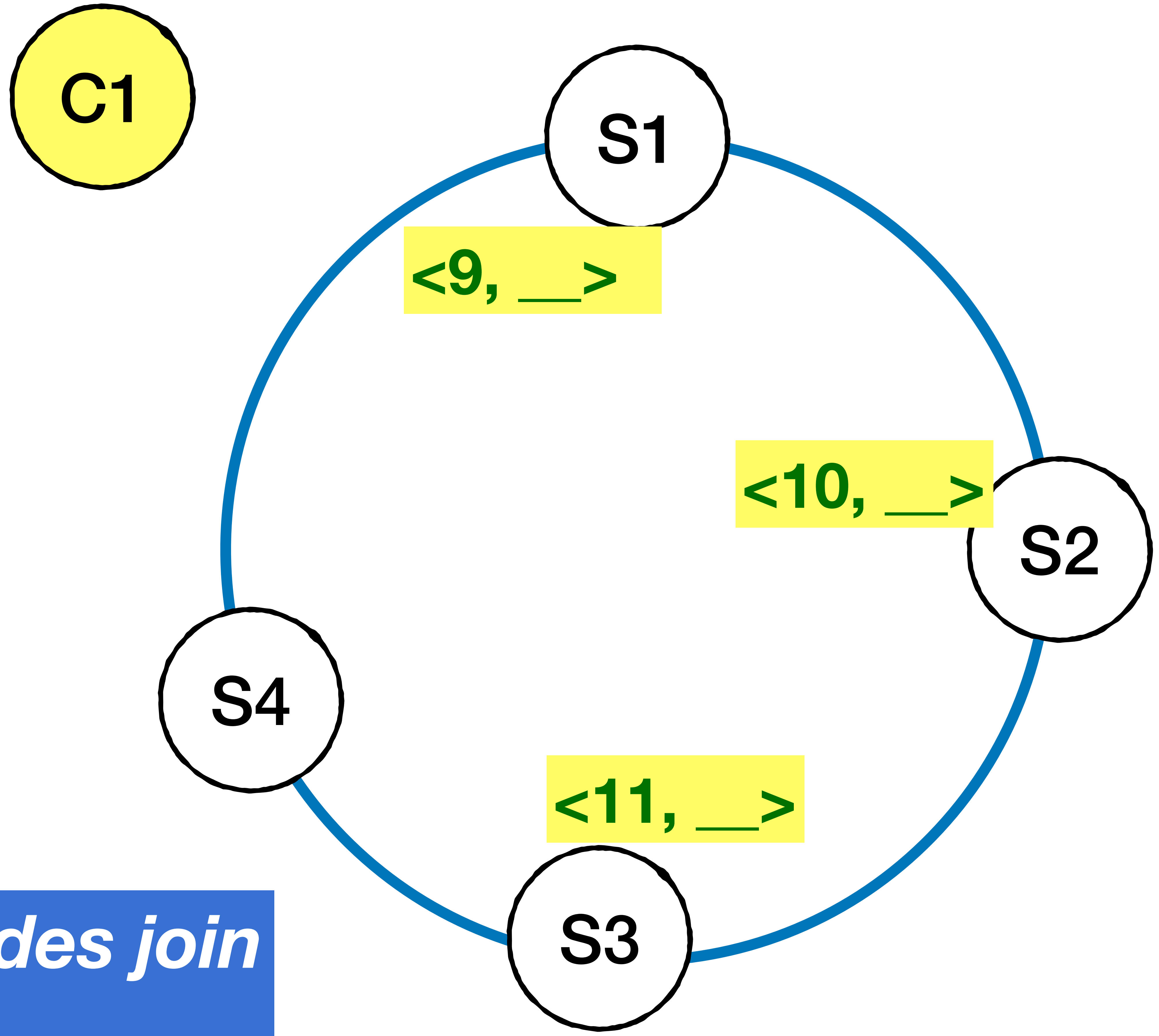

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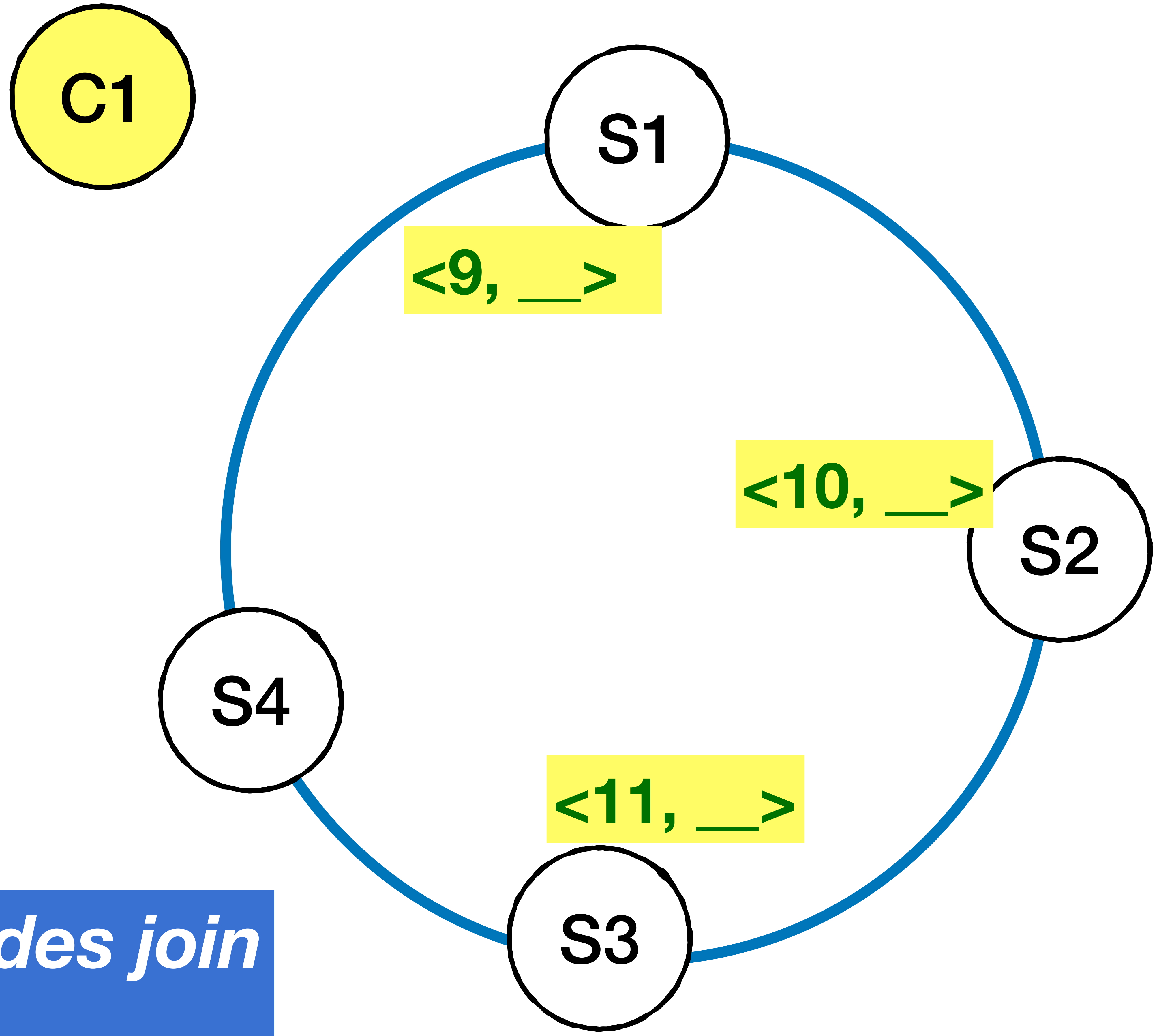

What happens when nodes join or leave?

Everything moved! :(

Motivation for consistent hashing

- Our goal: Distribute keys across dynamic servers while **minimizing remapping when the number of servers changes**
  - Balance load across servers
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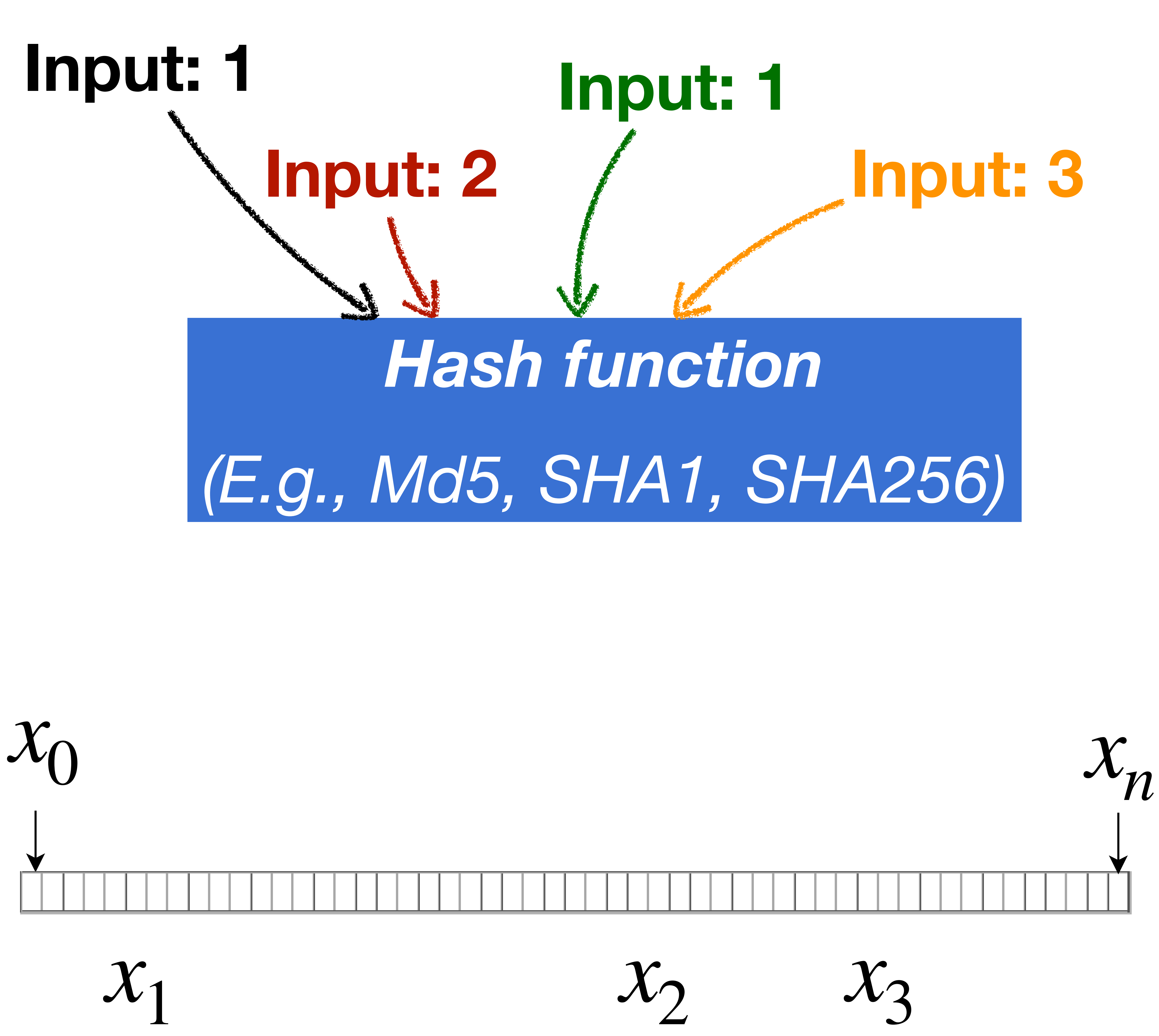
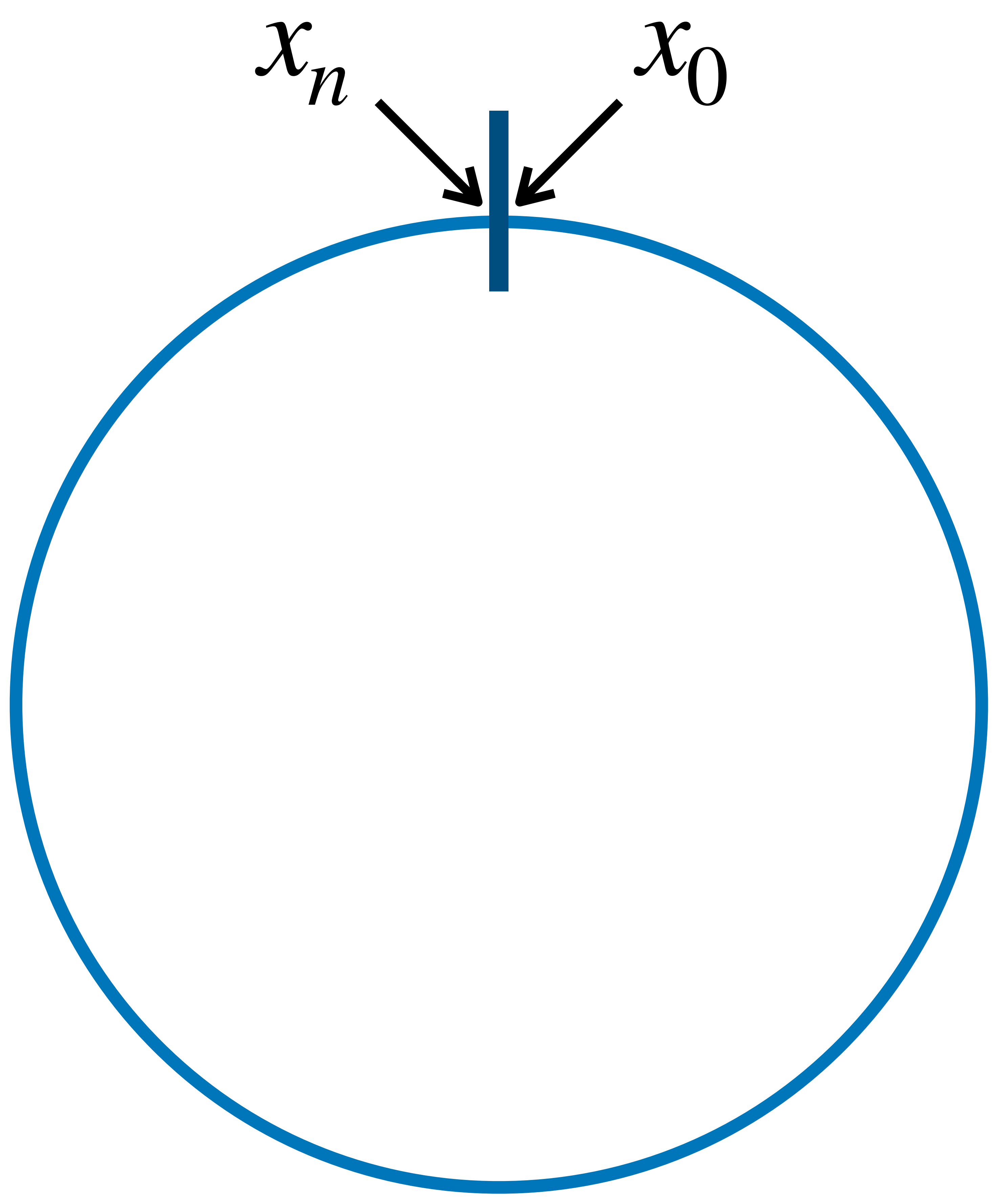
  - Support elasticity (scaling up/down)
  - Localize failure impact

Hash space and hash ring





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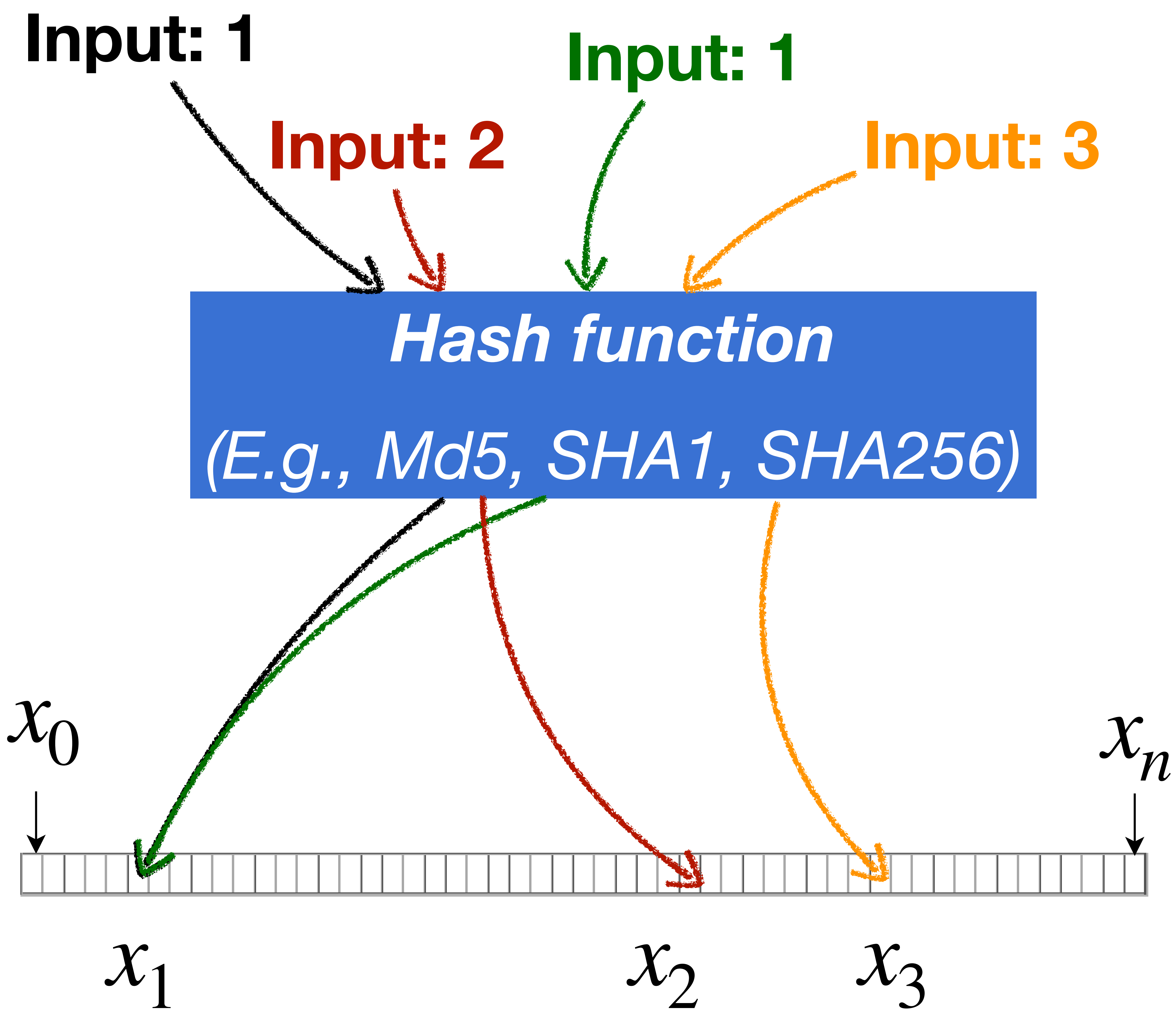

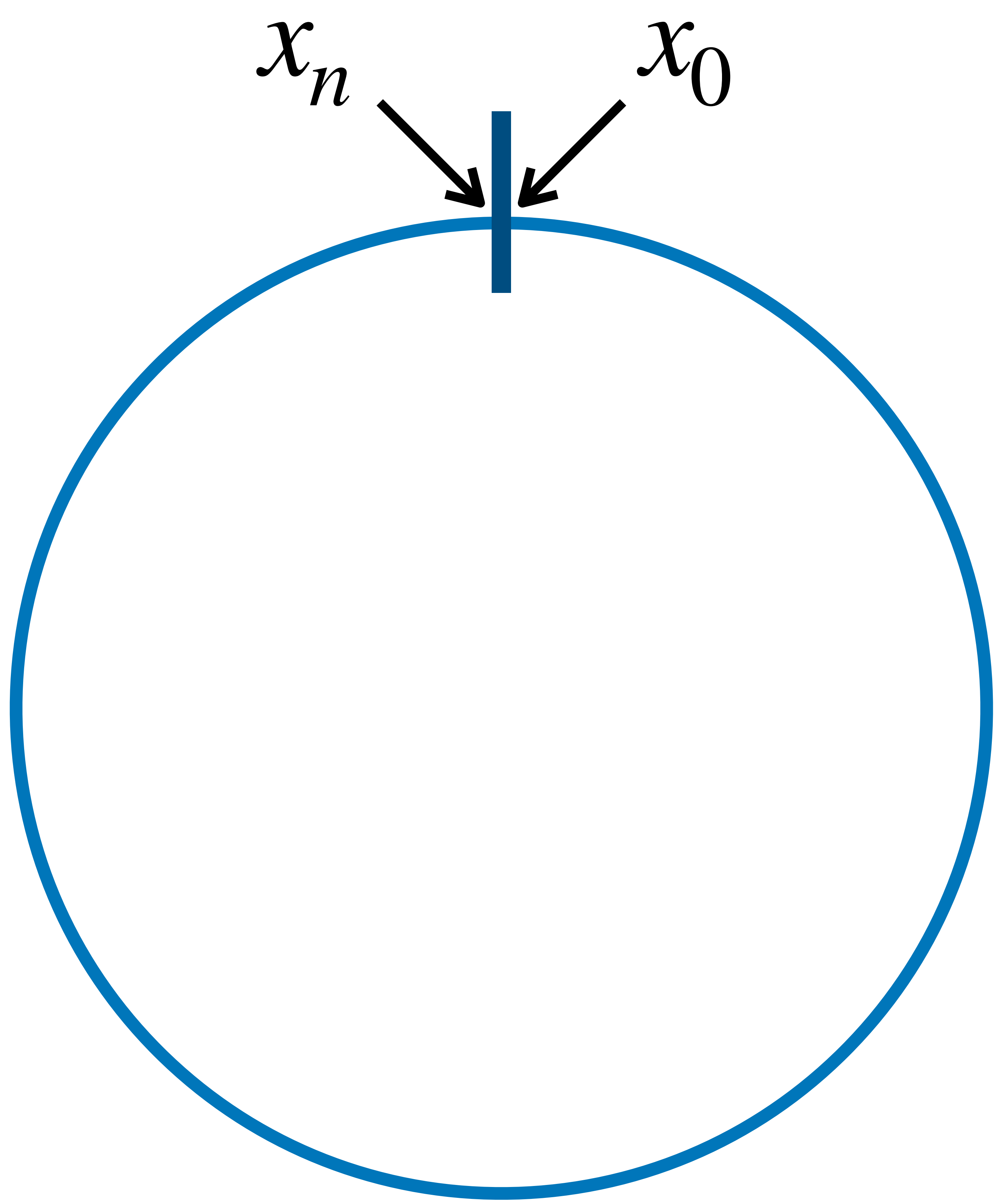

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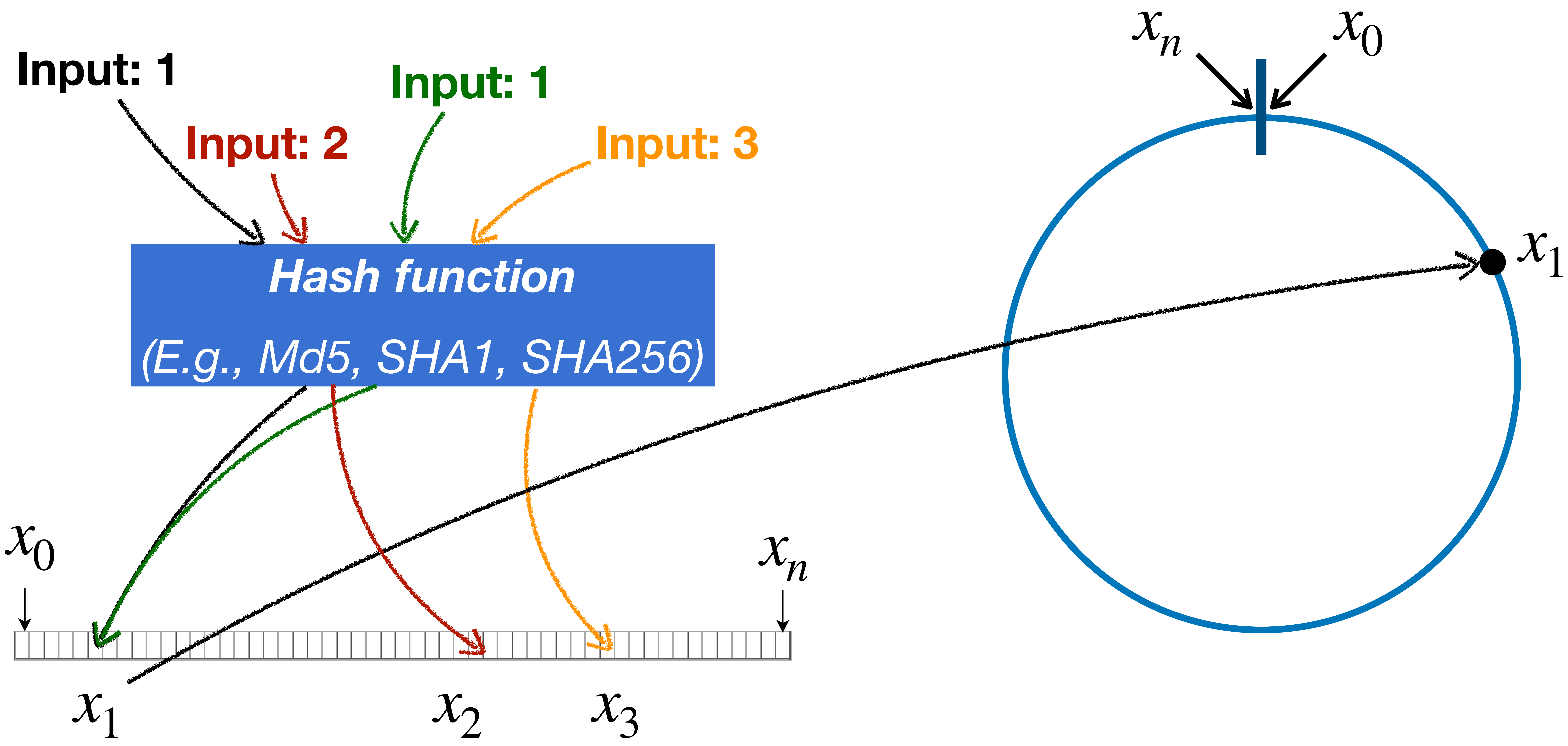

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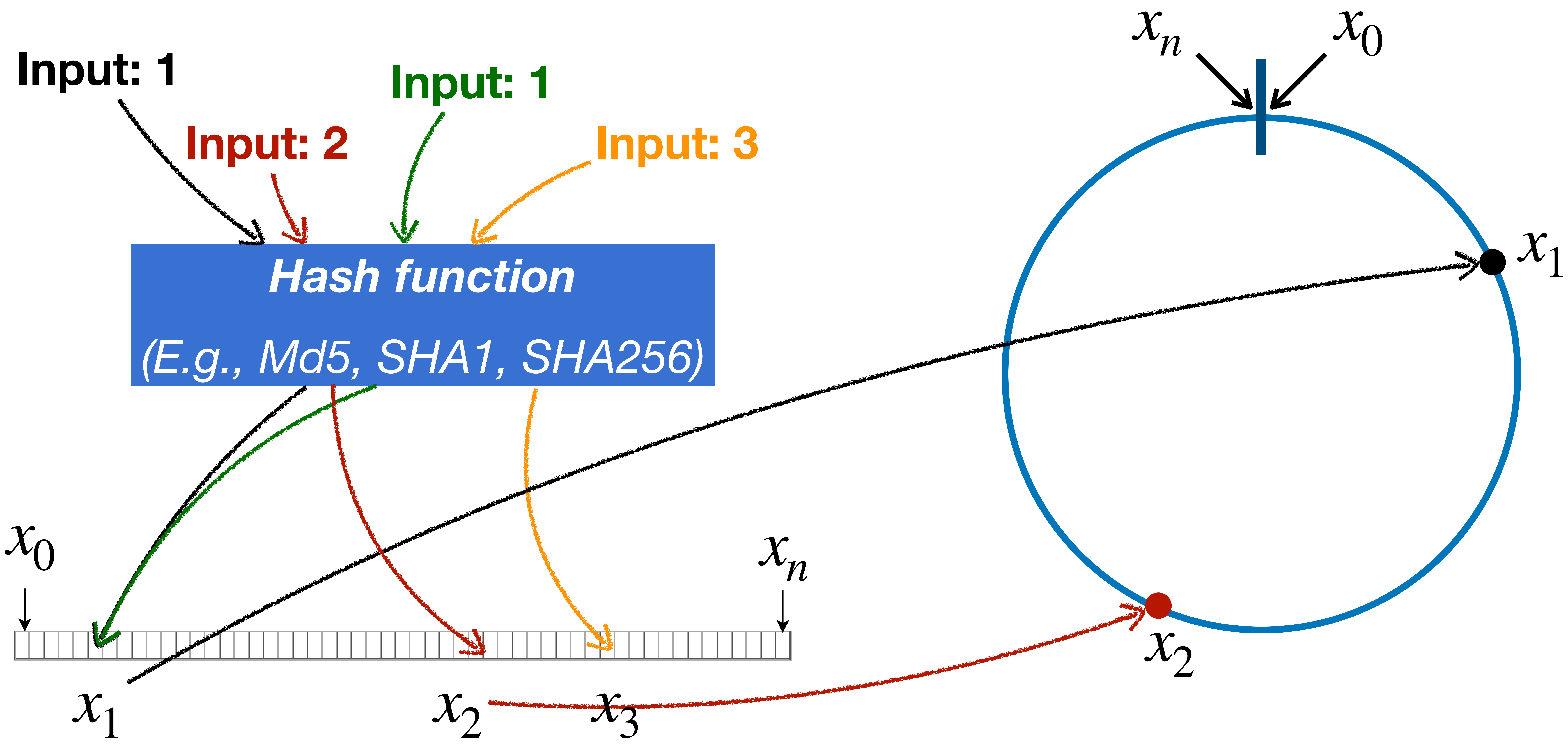

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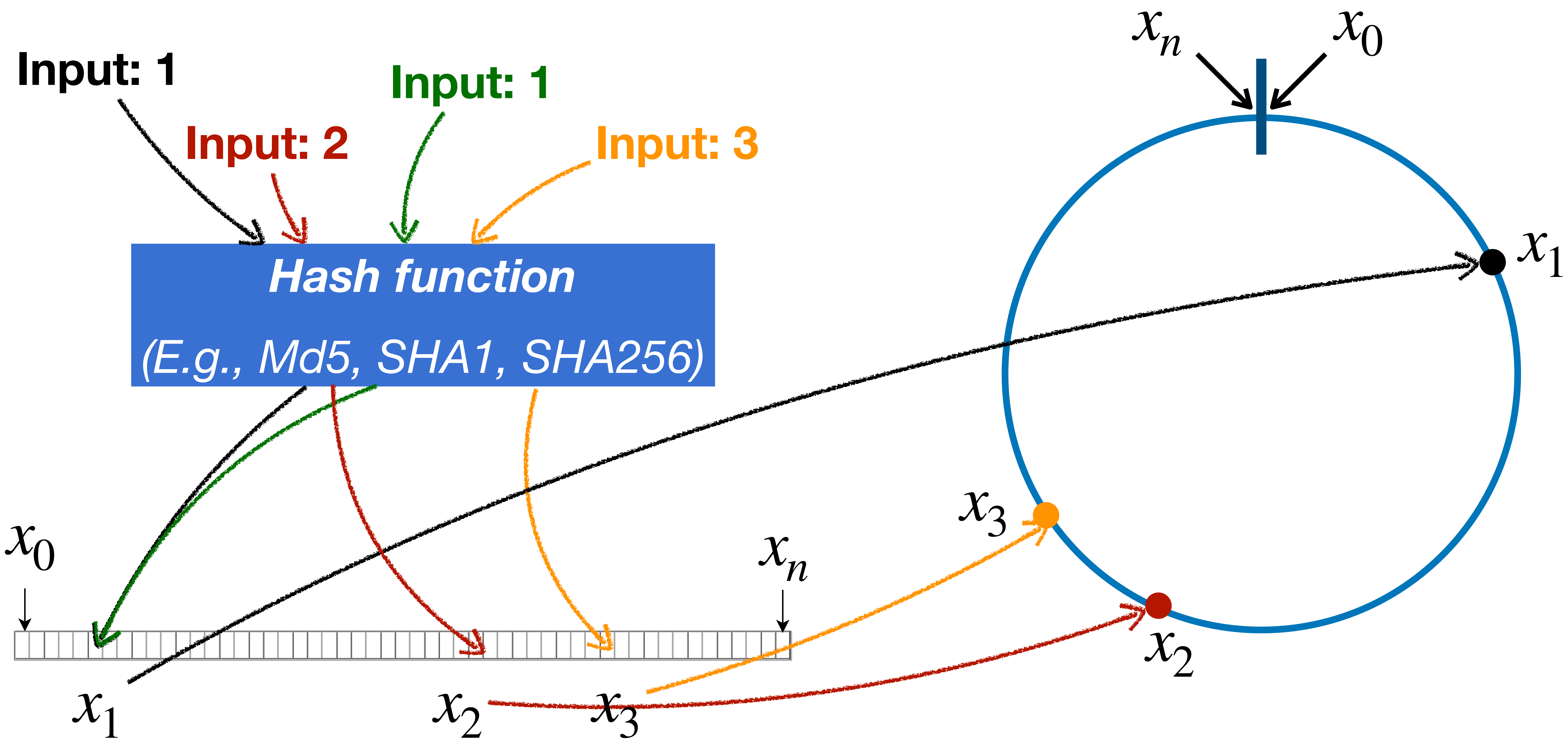
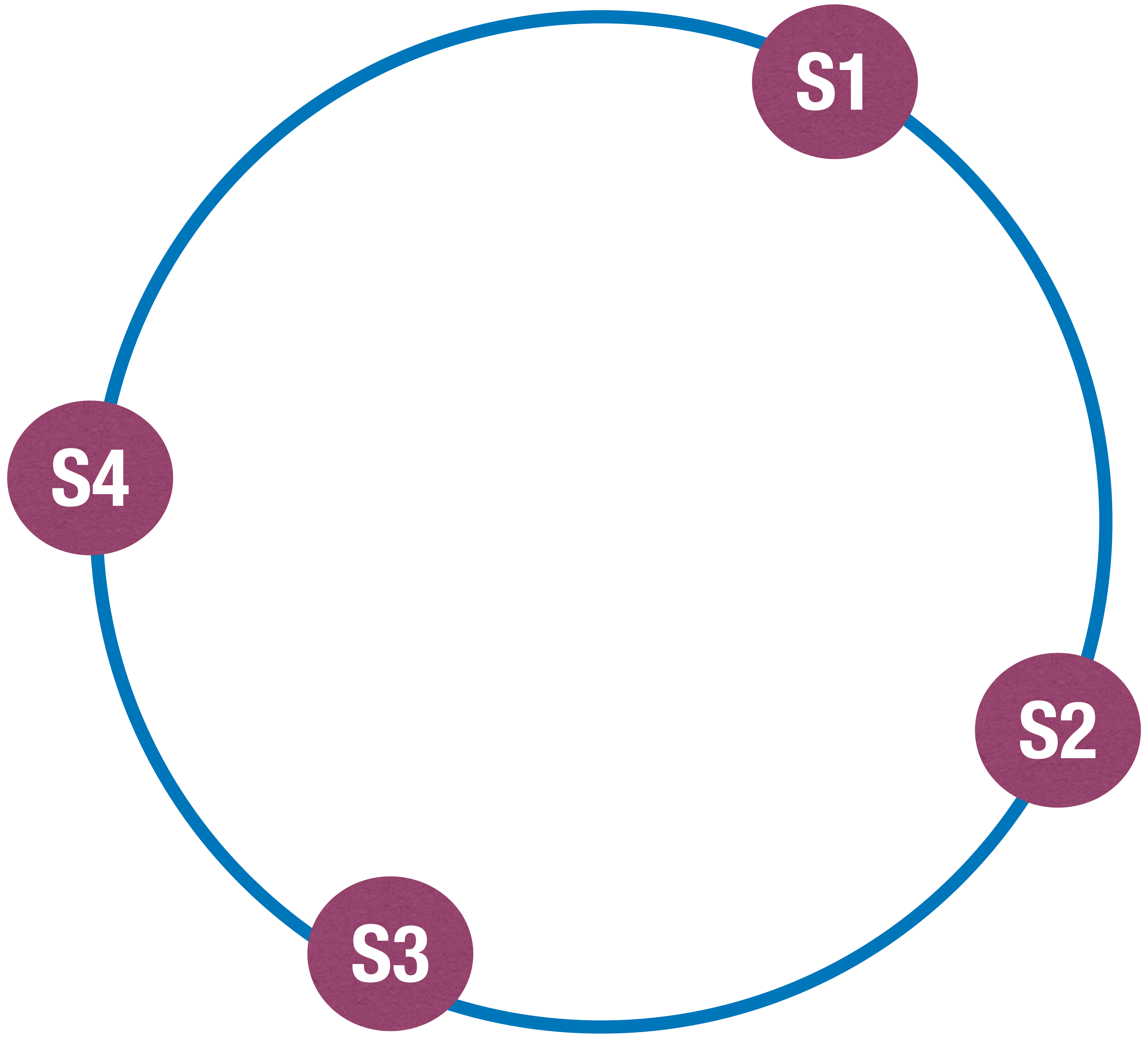


Consistent hashing

Step 1: Hash servers

- (E.g, using their IPs)



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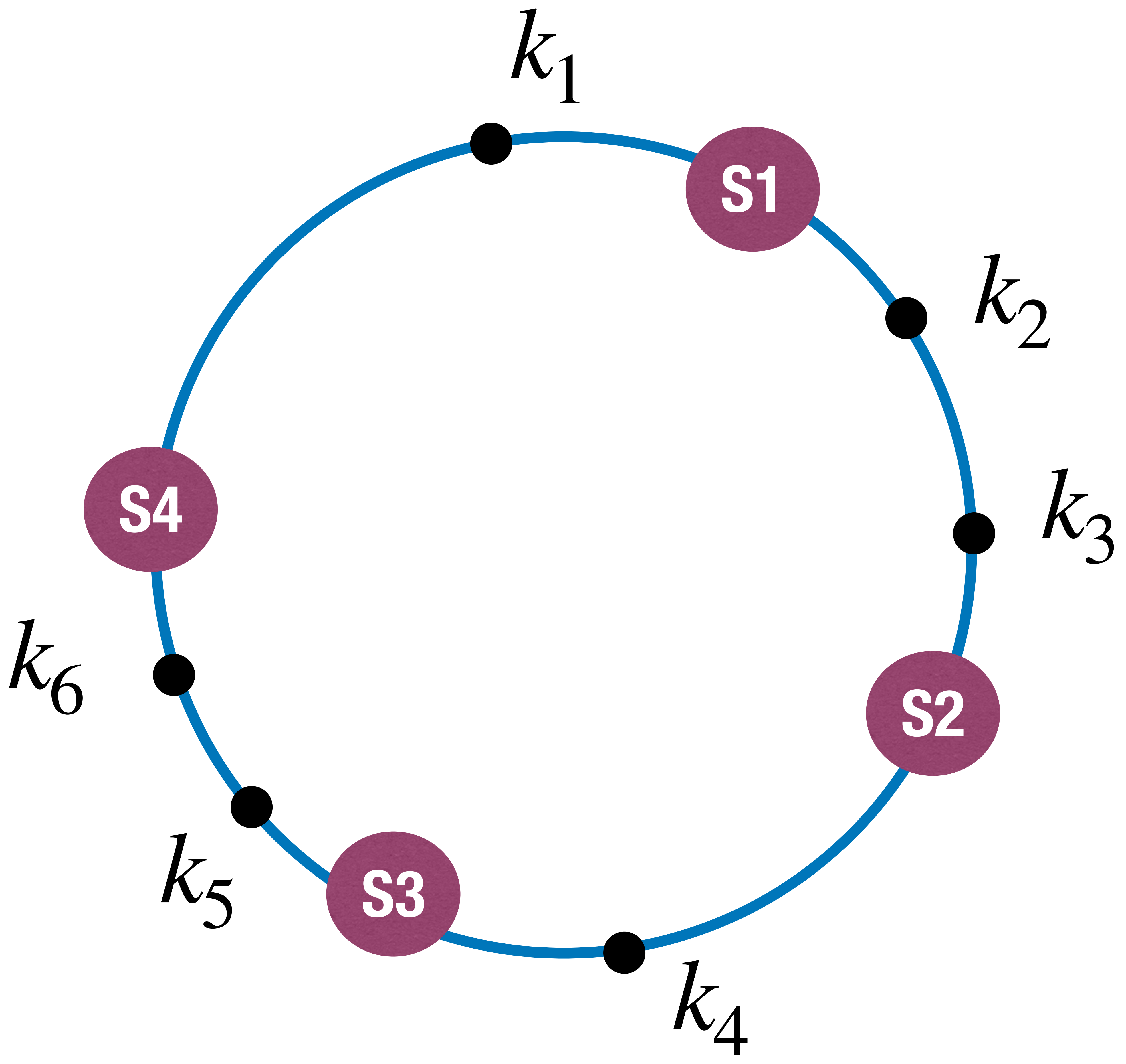

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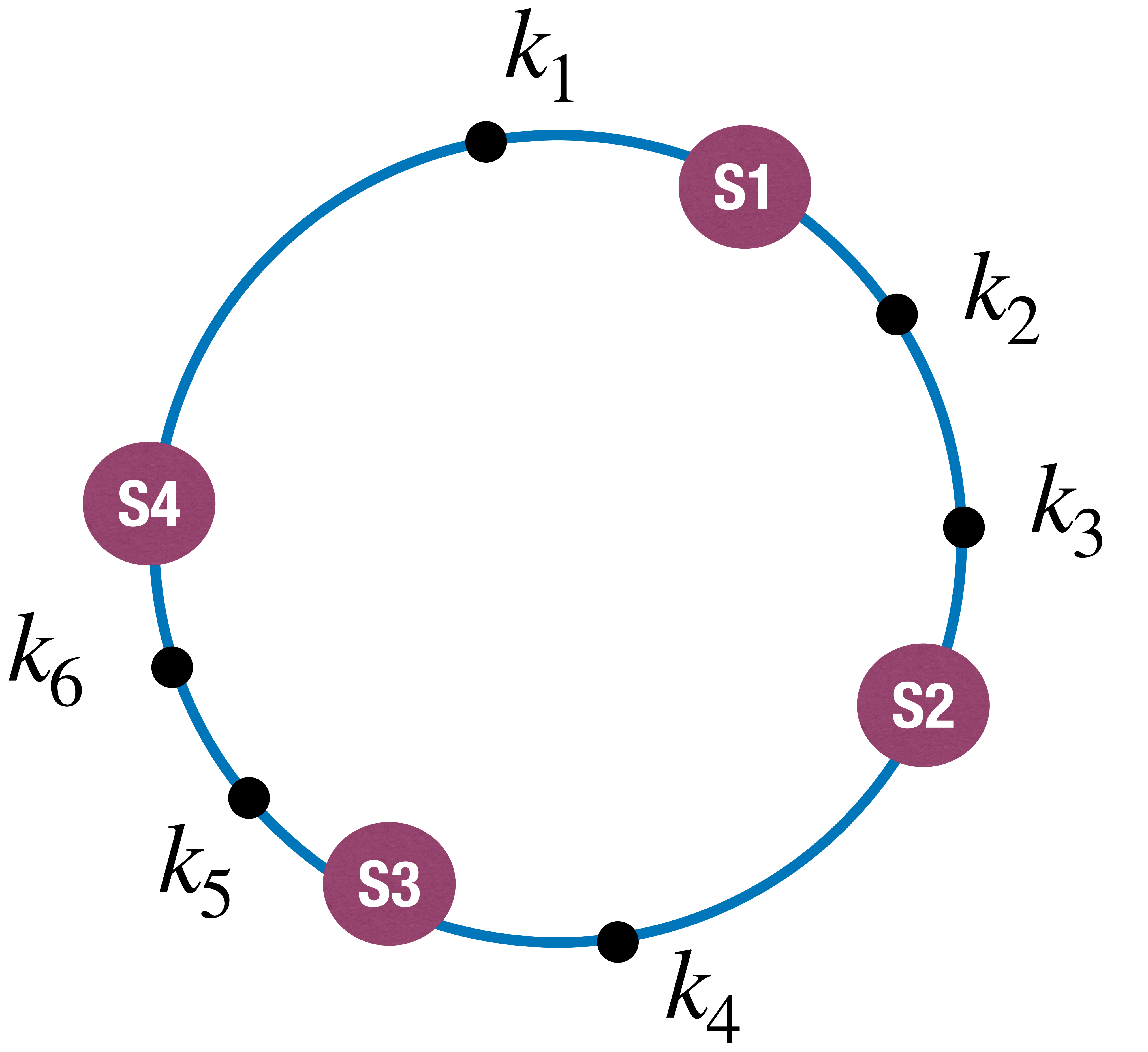
To determine which server a key is stored on, go clockwise from the key position on the ring until a server is found



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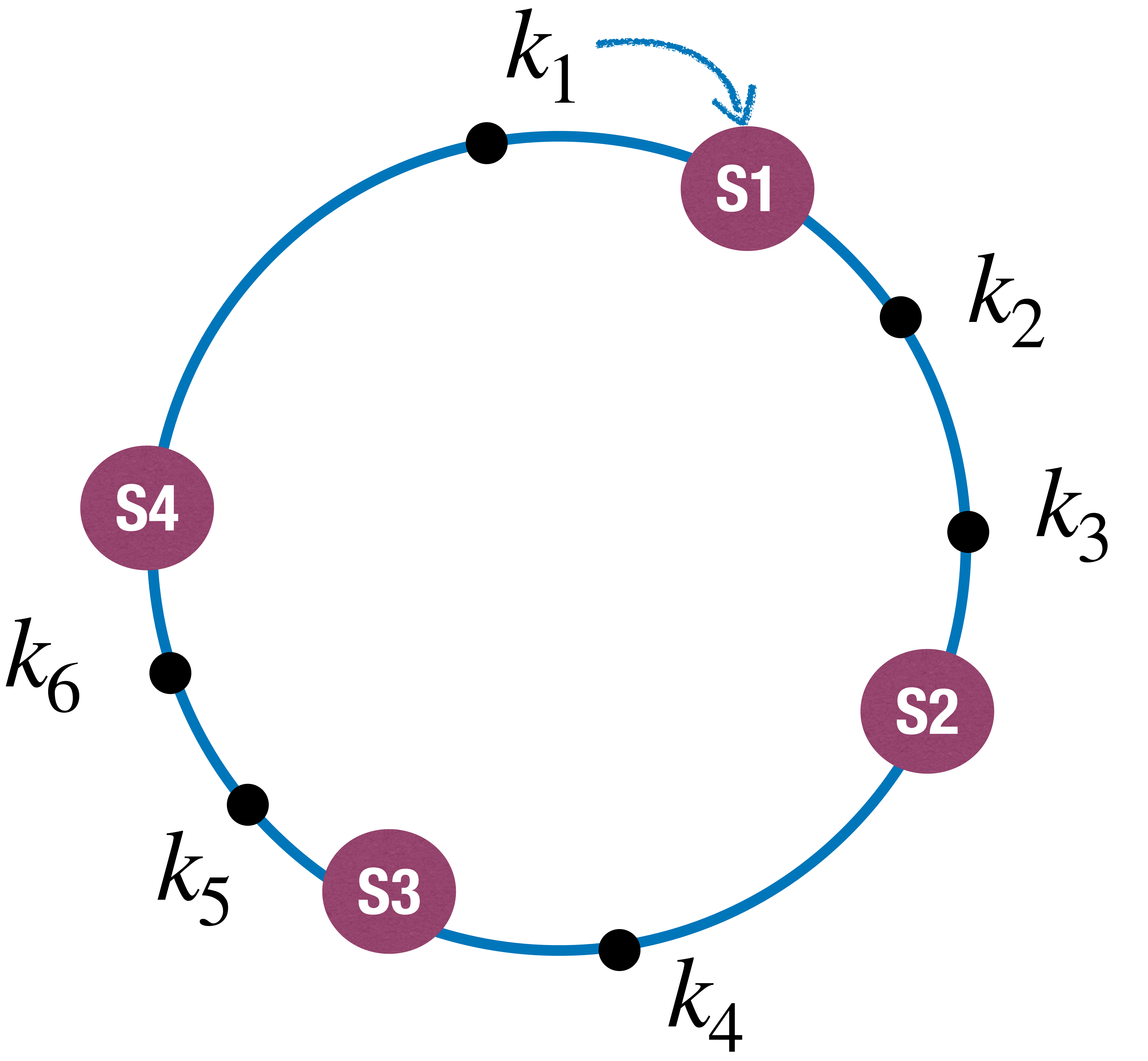

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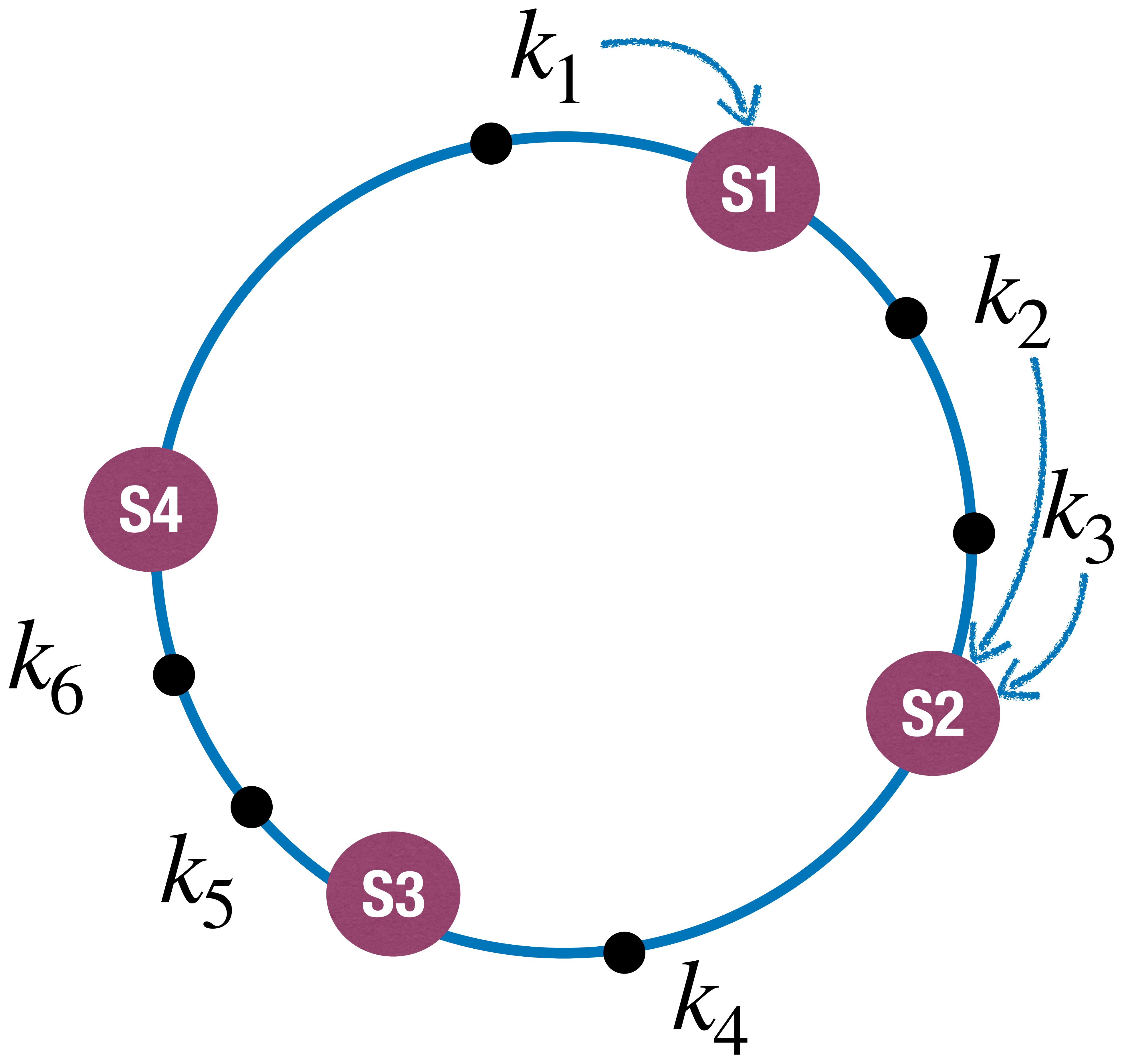

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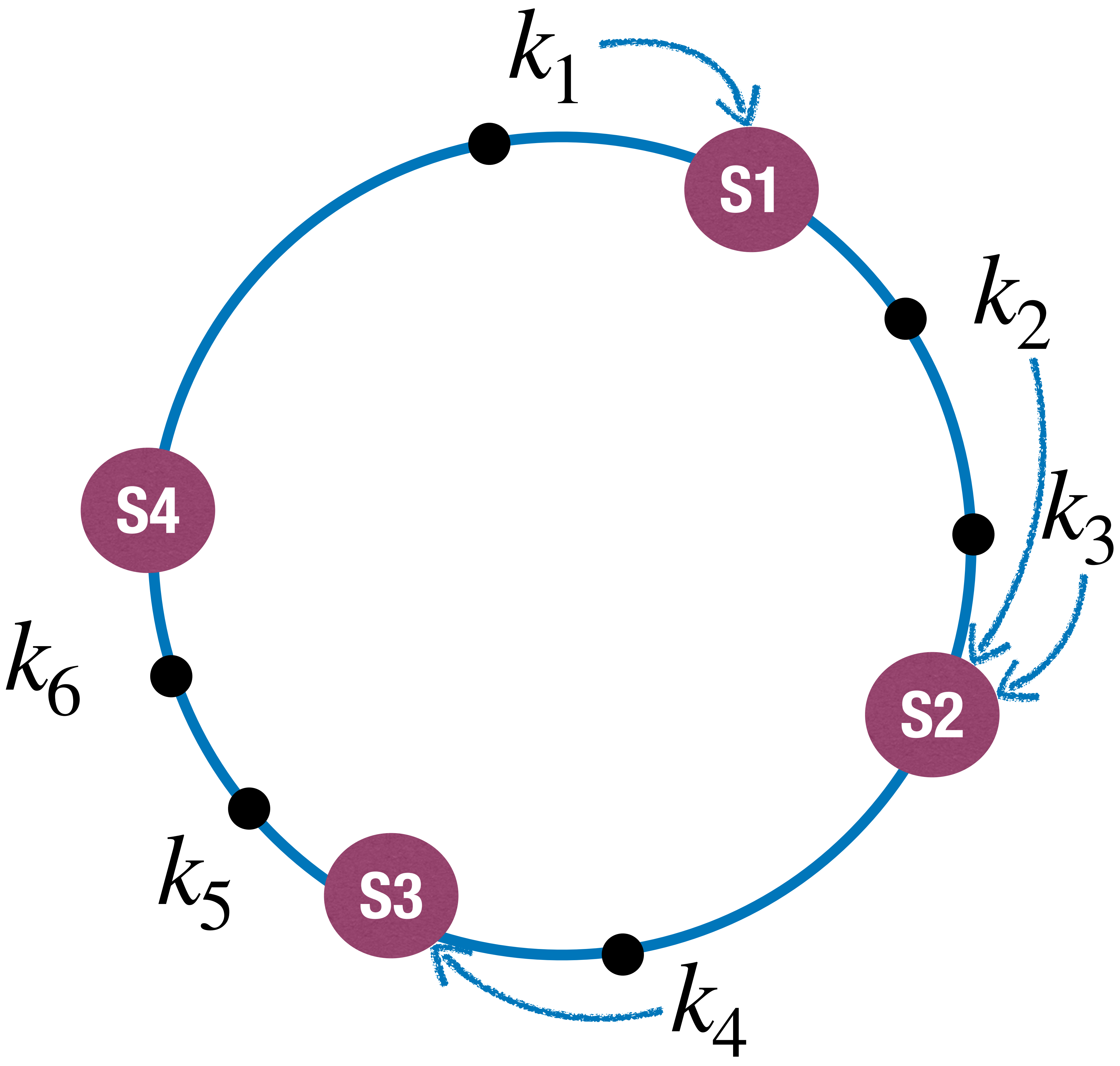

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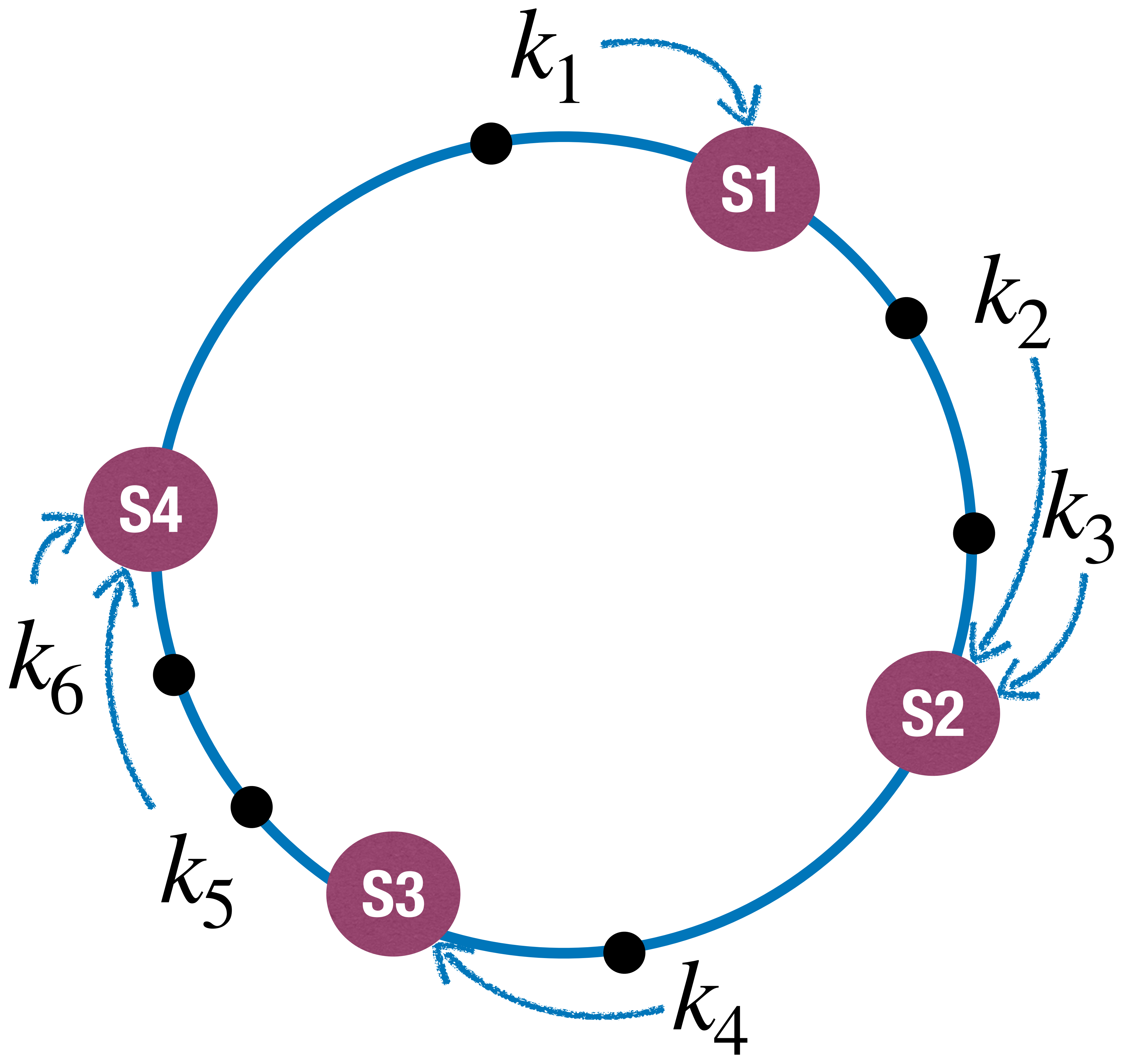

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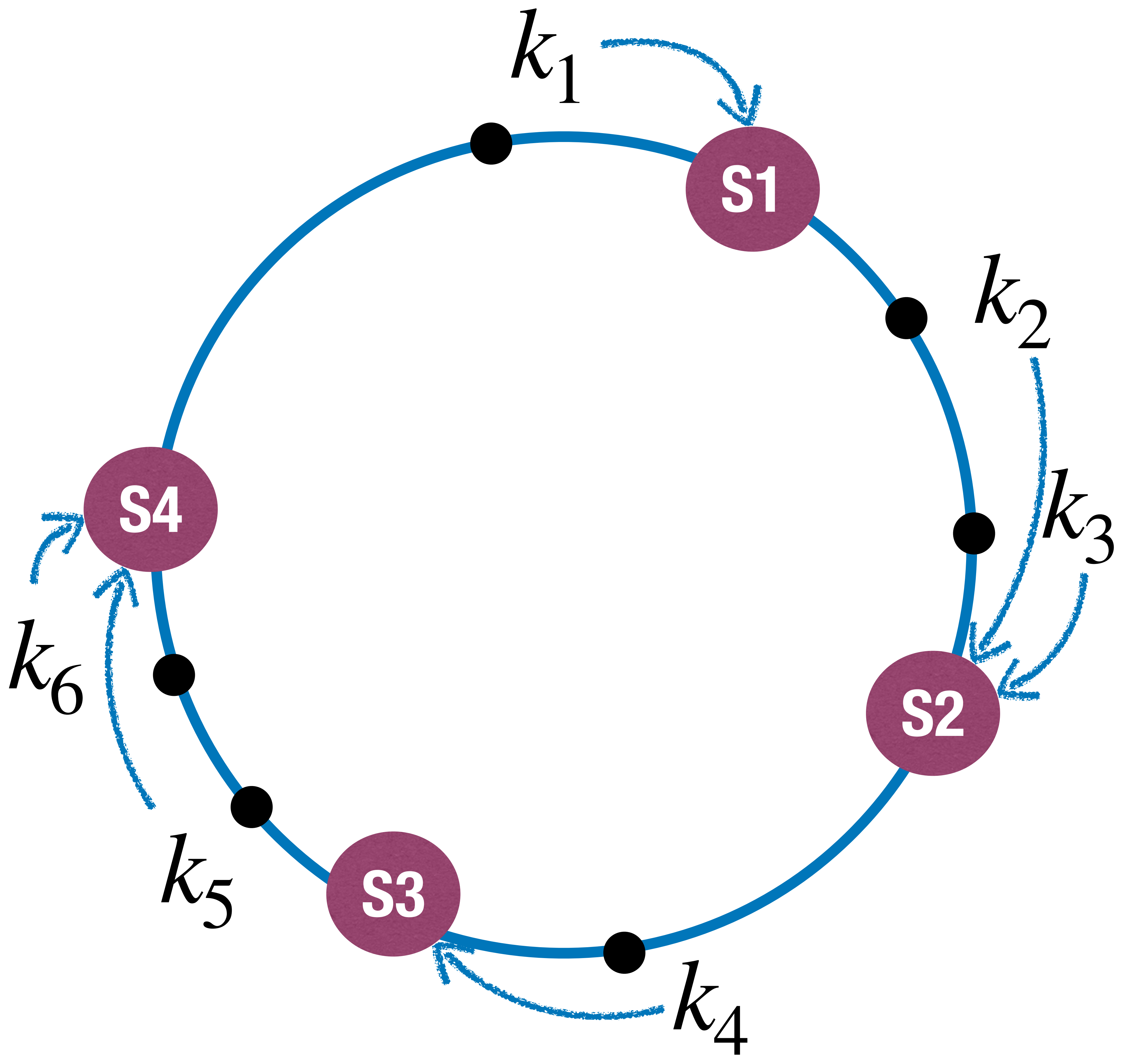

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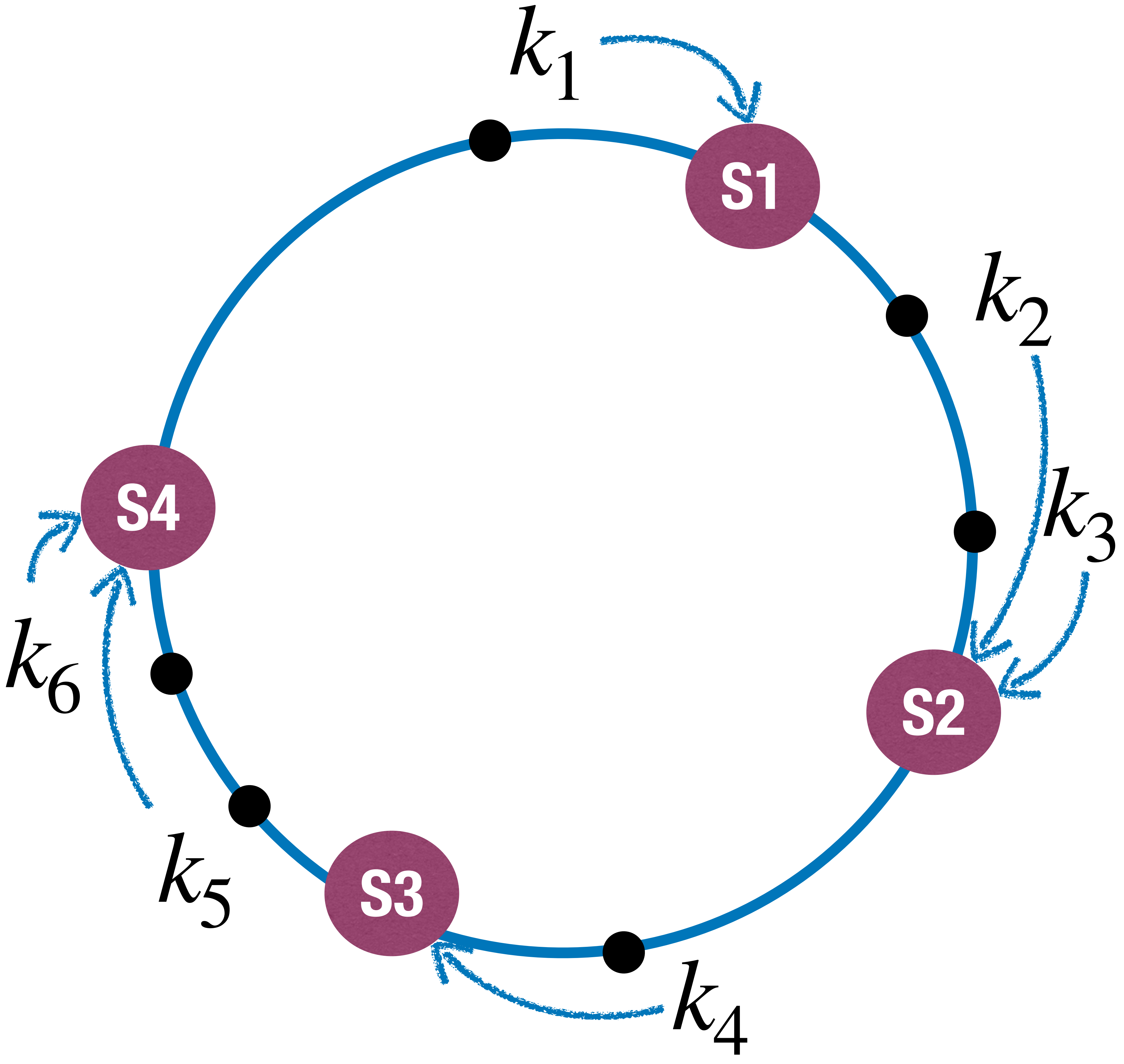

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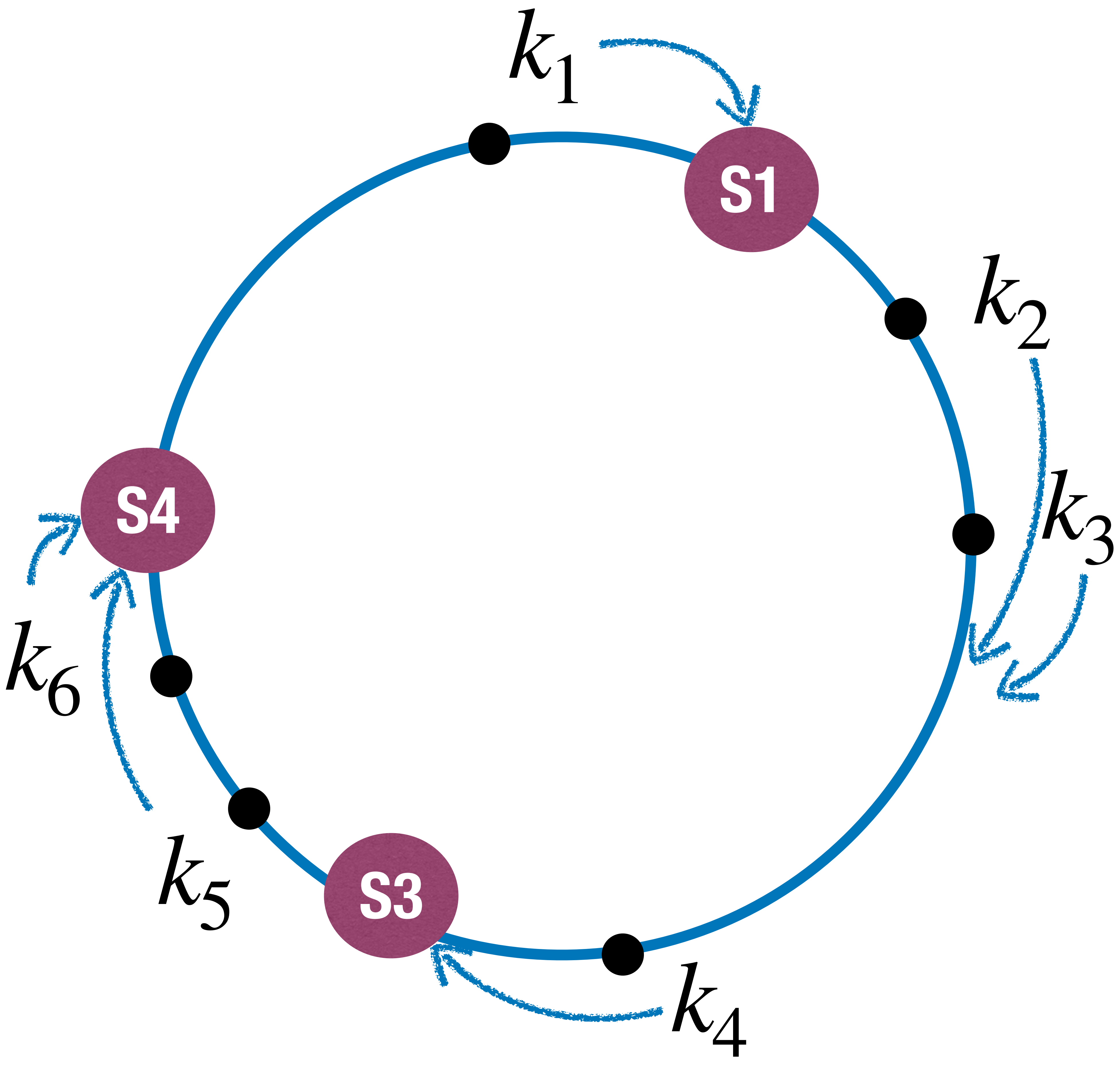

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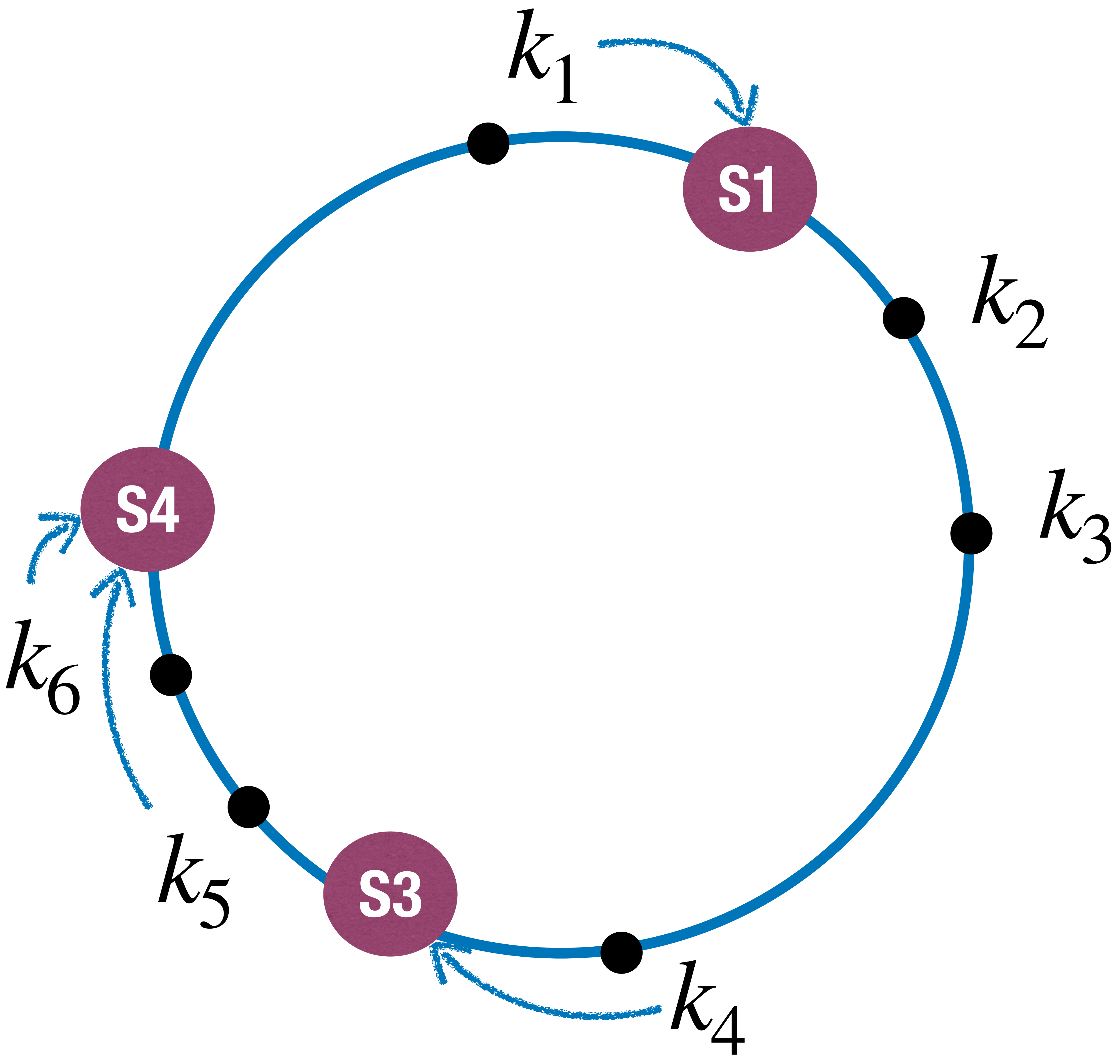

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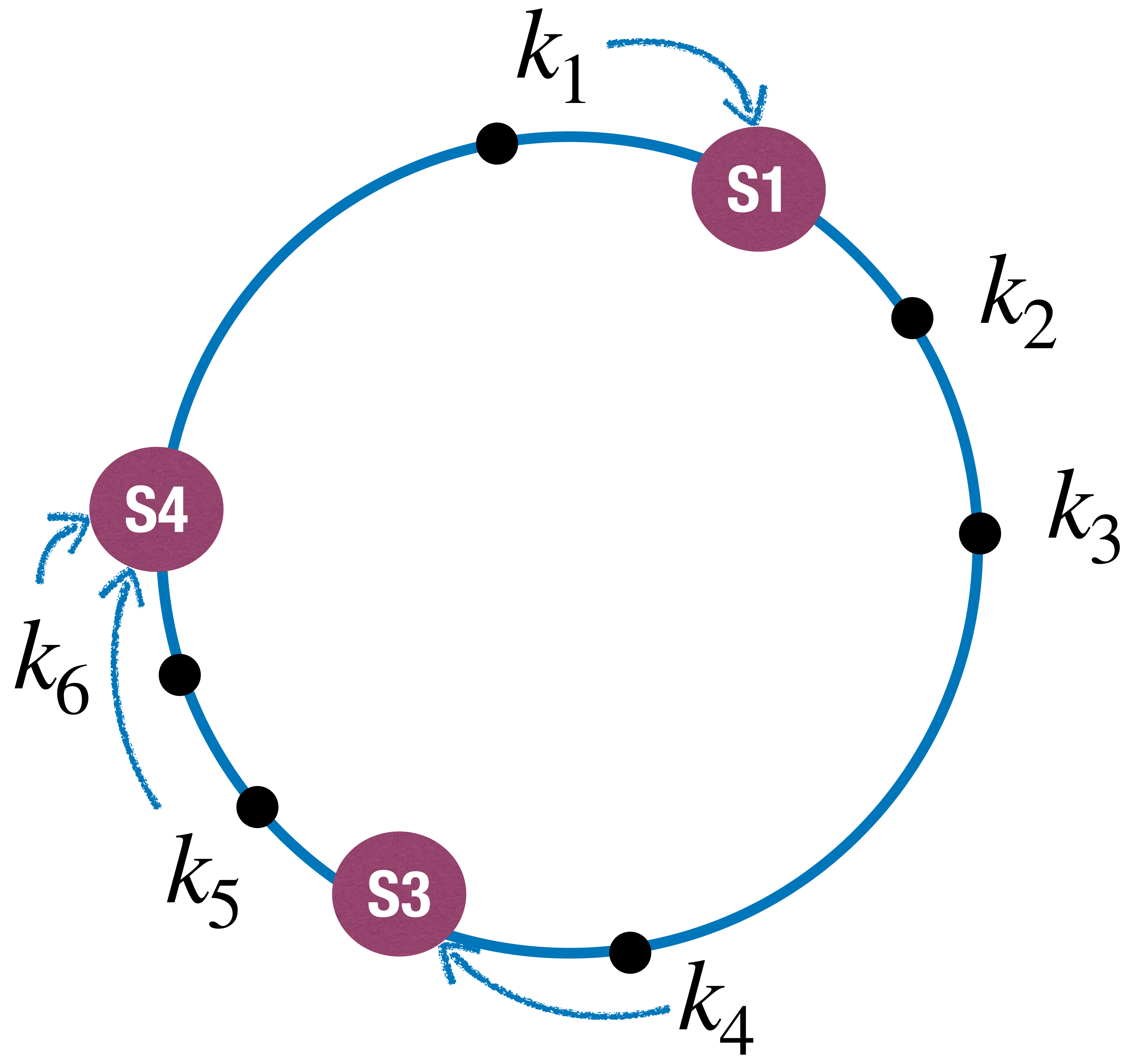

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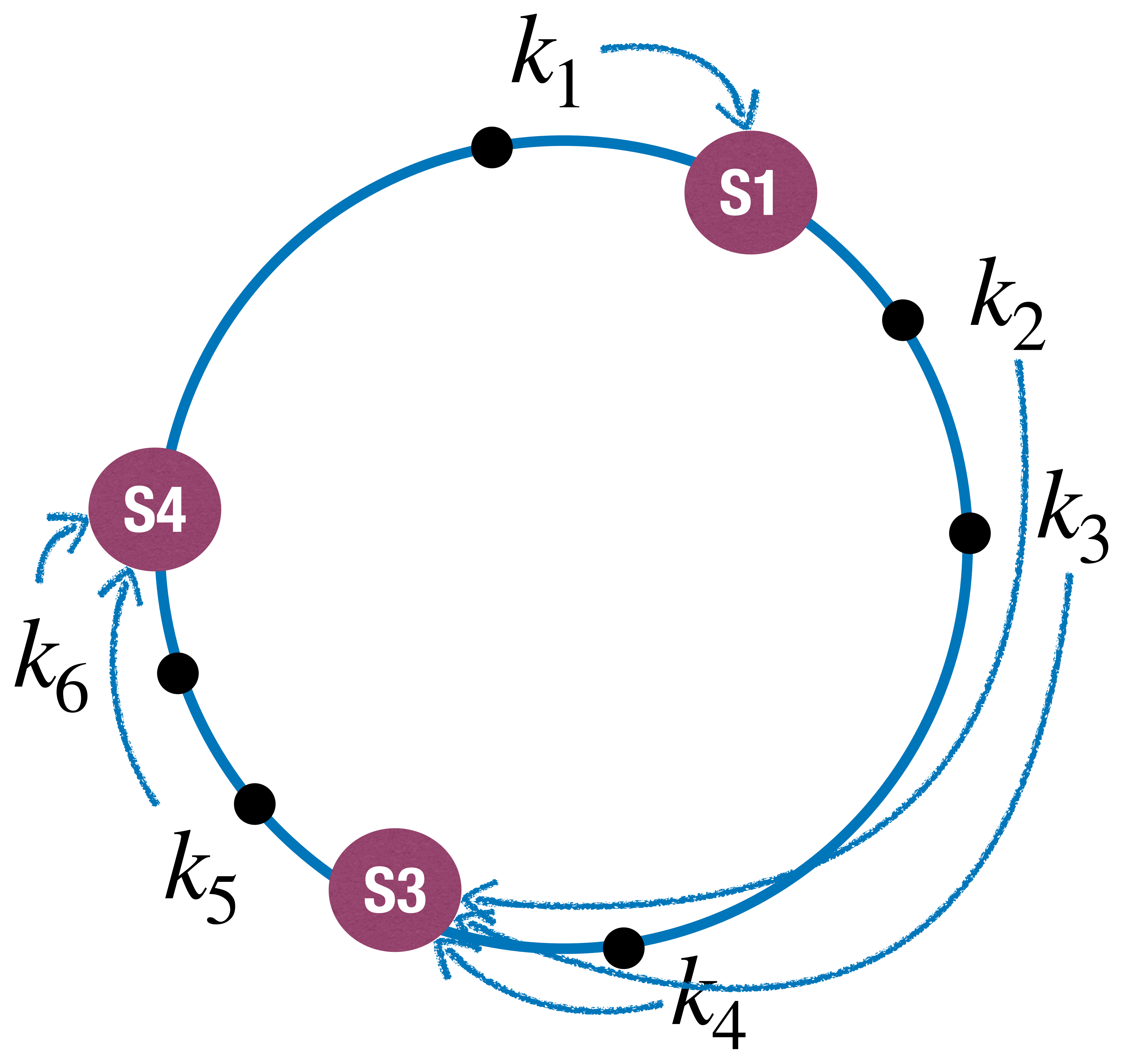

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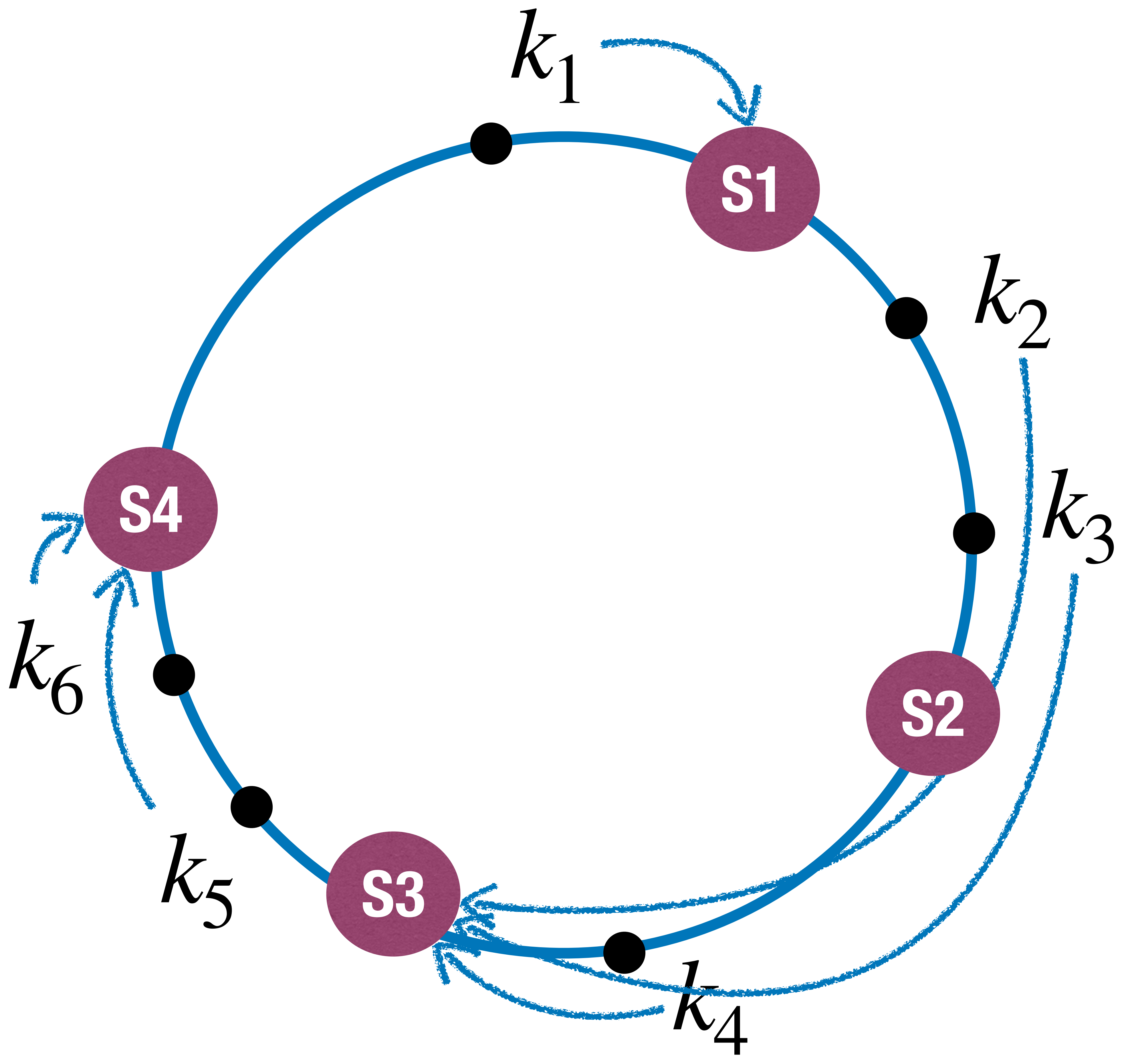

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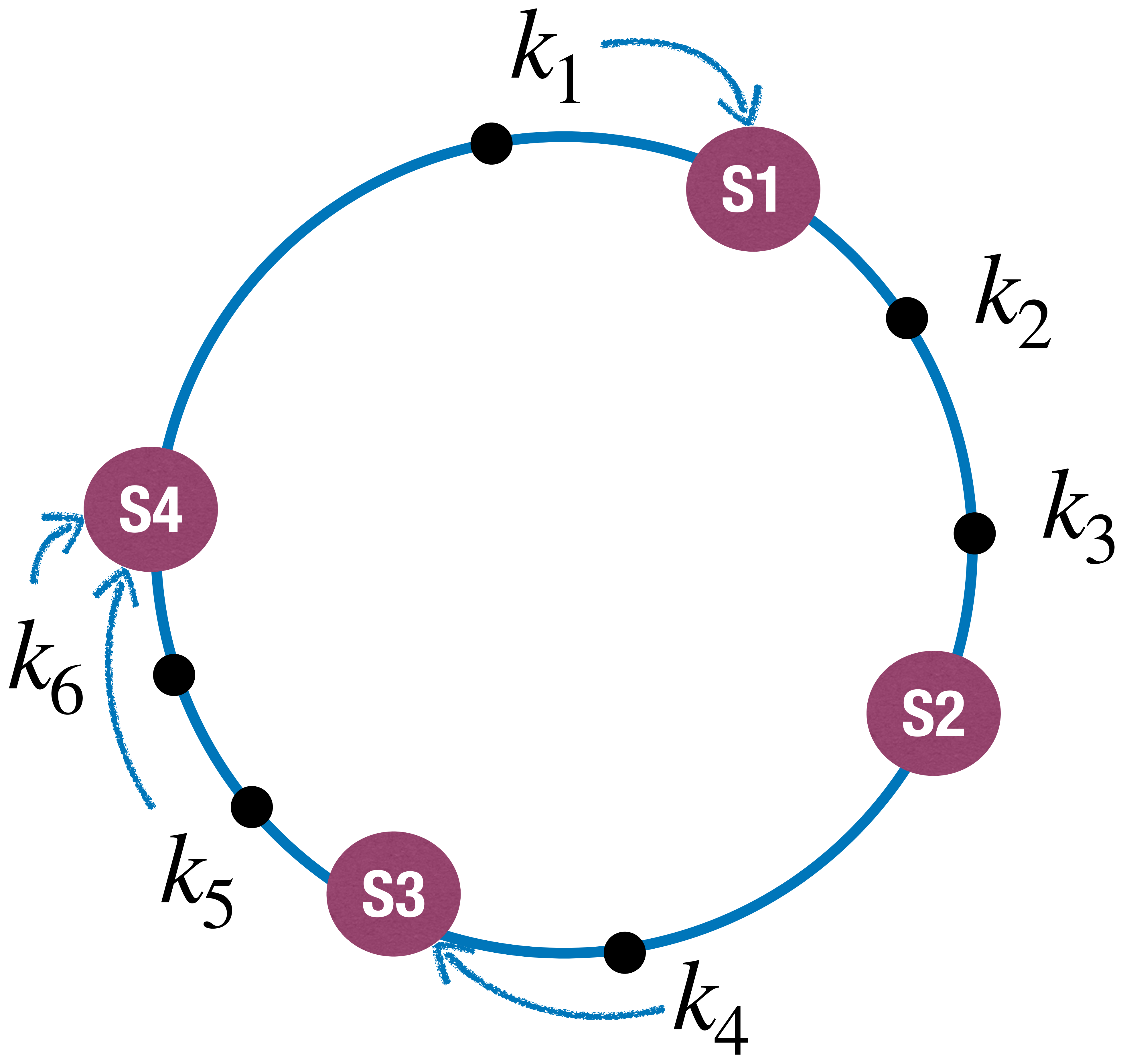

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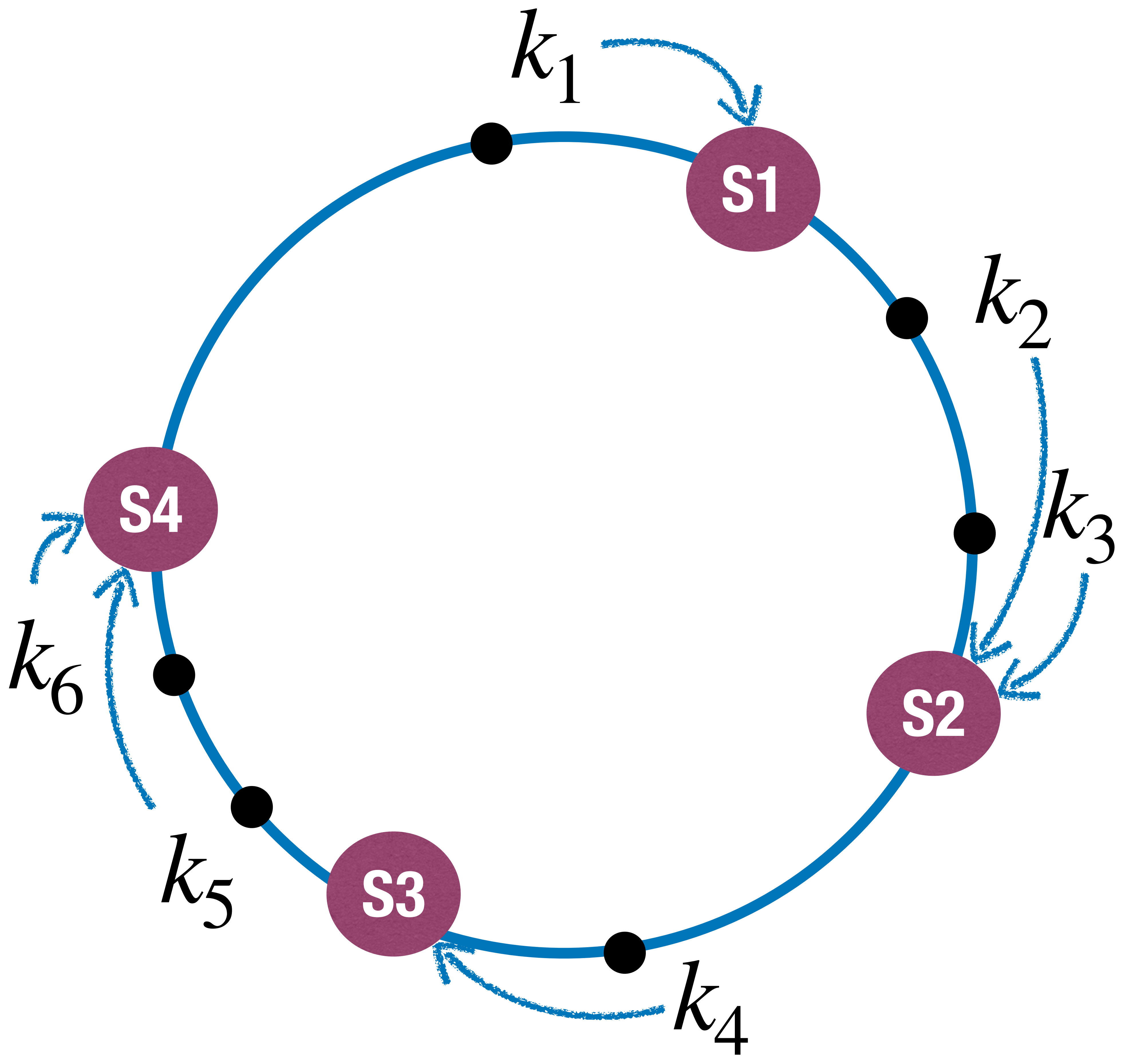

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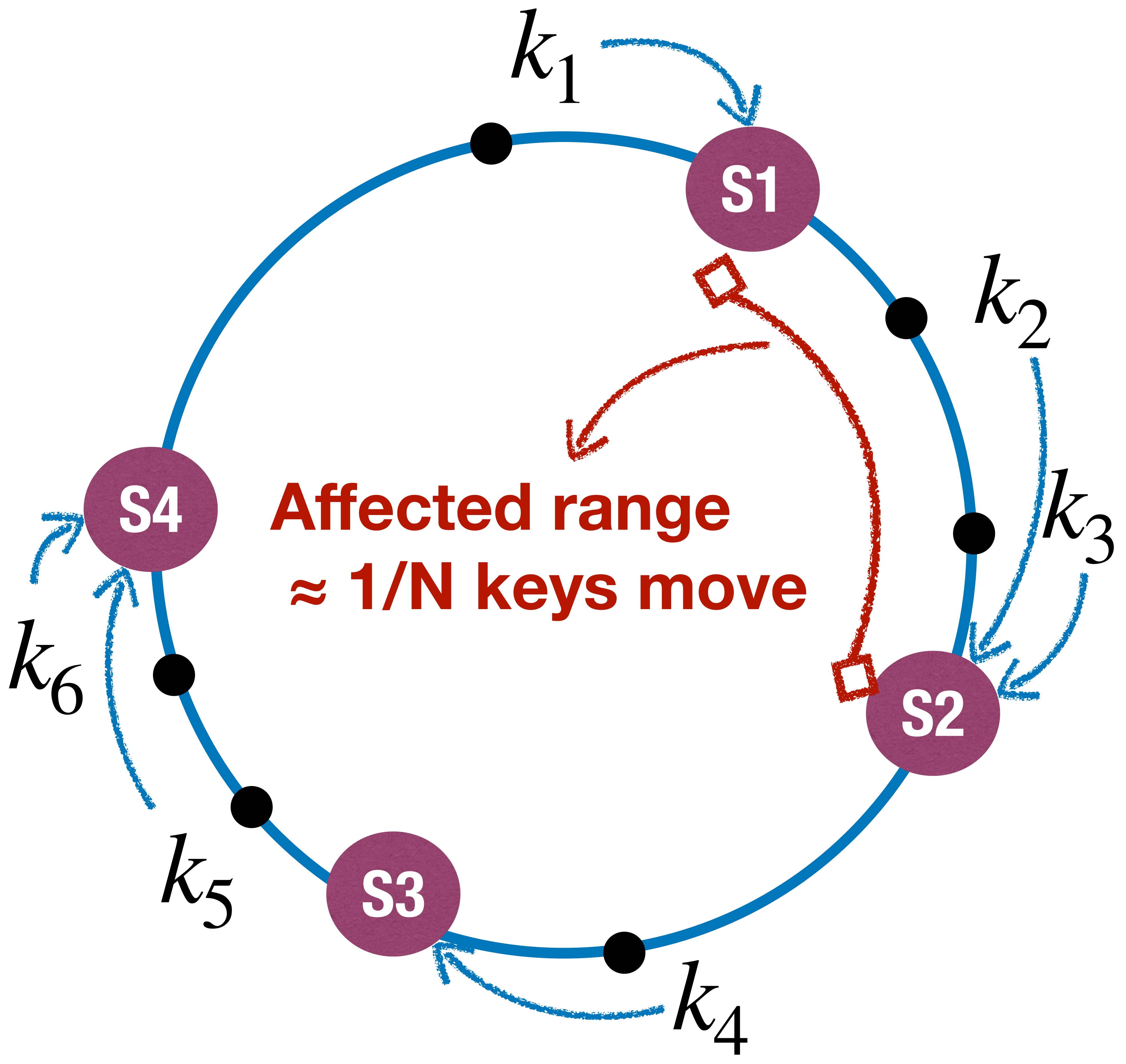
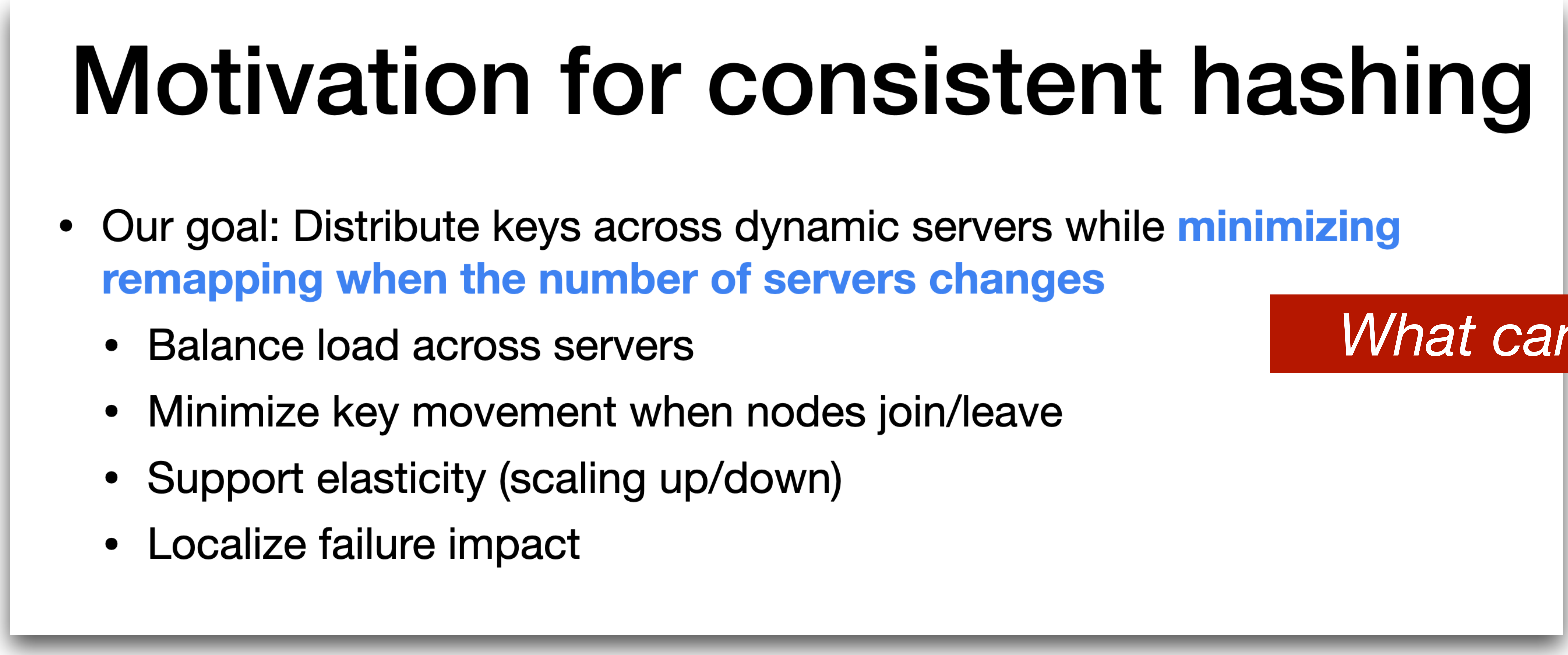


Recall our goal. Is it perfect?



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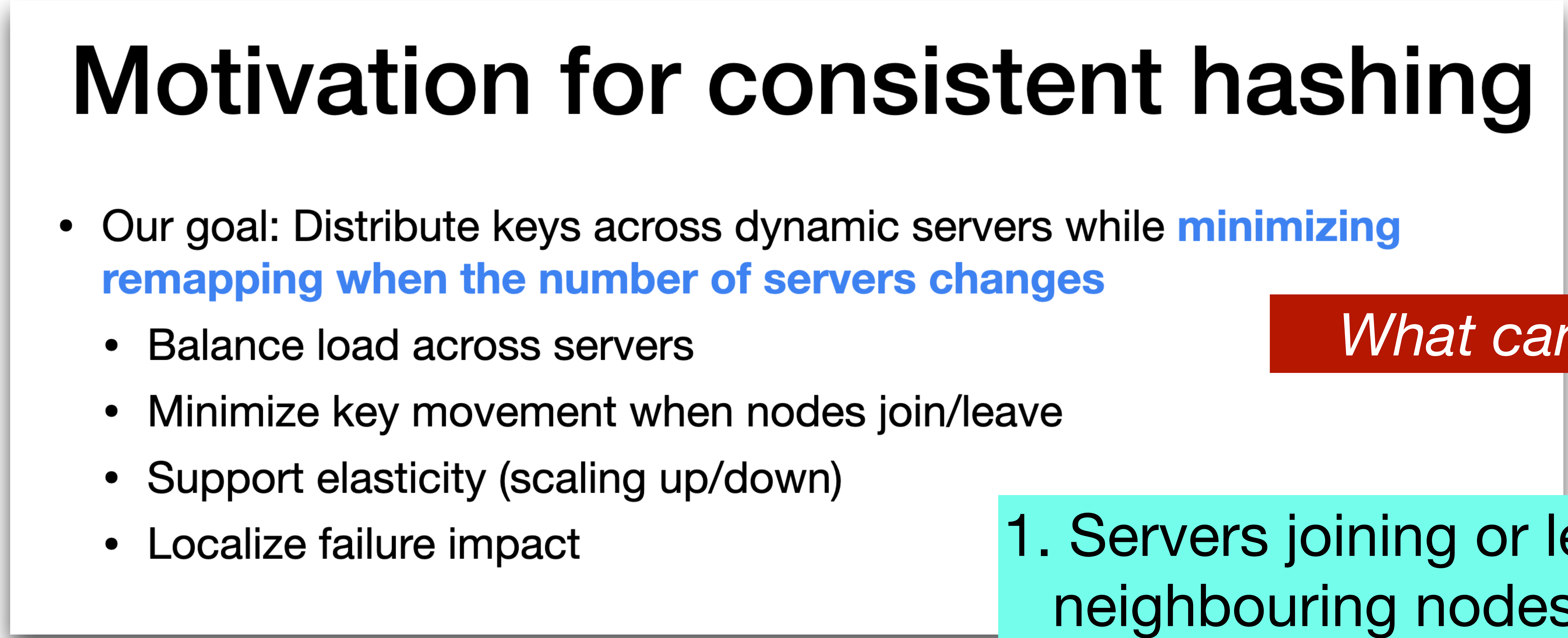

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What can go wrong ?

1. Servers joining or leaving shift loads to neighbouring nodes
2. Workload characteristic may not uniformly distribute the load across nodes

Recall memory management in OS

- Recall how one of the key concepts in Operating Systems
  - How do we manage memory?

Memory without virtualization

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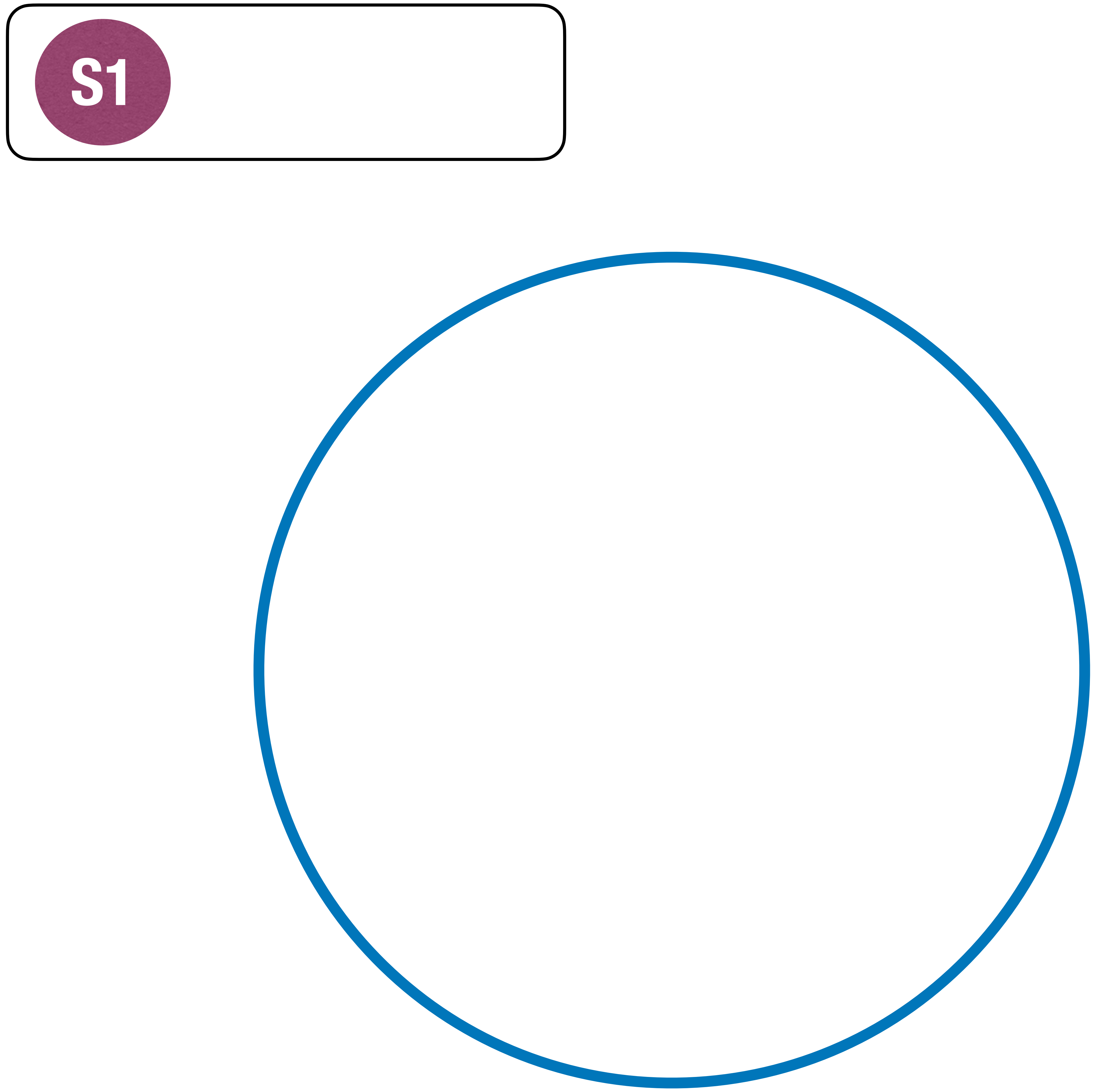
Adding virtual memory

- Break memory into fixed-size pages
- Create virtual pages
- Map virtual to physical frames via page table
- Fine-grained load distribution

Similarly, adding virtual nodes to hash ring

- Virtual nodes (vnodes) are multiple logical positions on the hash ring that map to the same physical server.
  - N = # of physical servers
  - V = # of virtual nodes per server
  - Total positions on ring: $N \times V$



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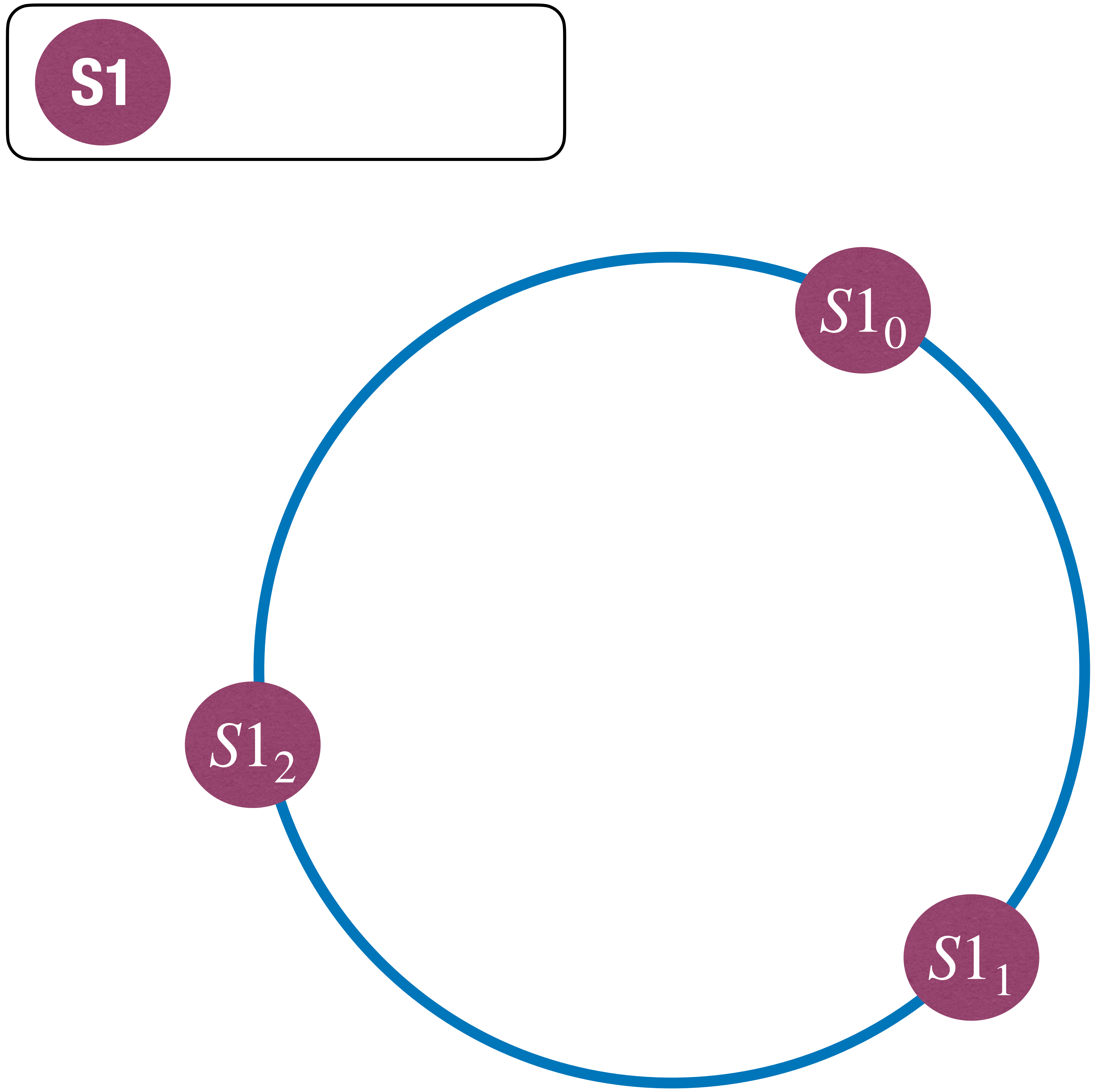

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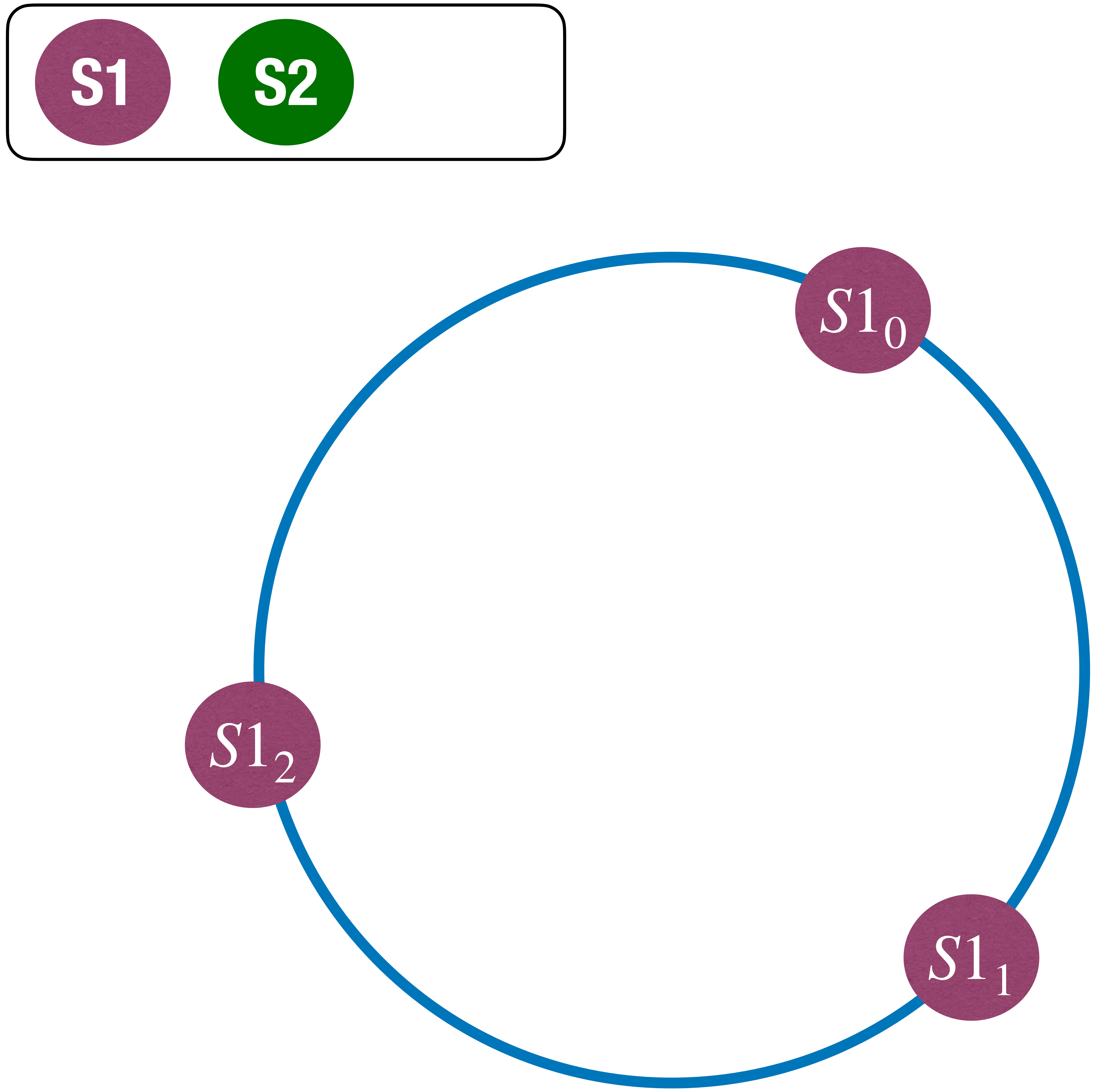

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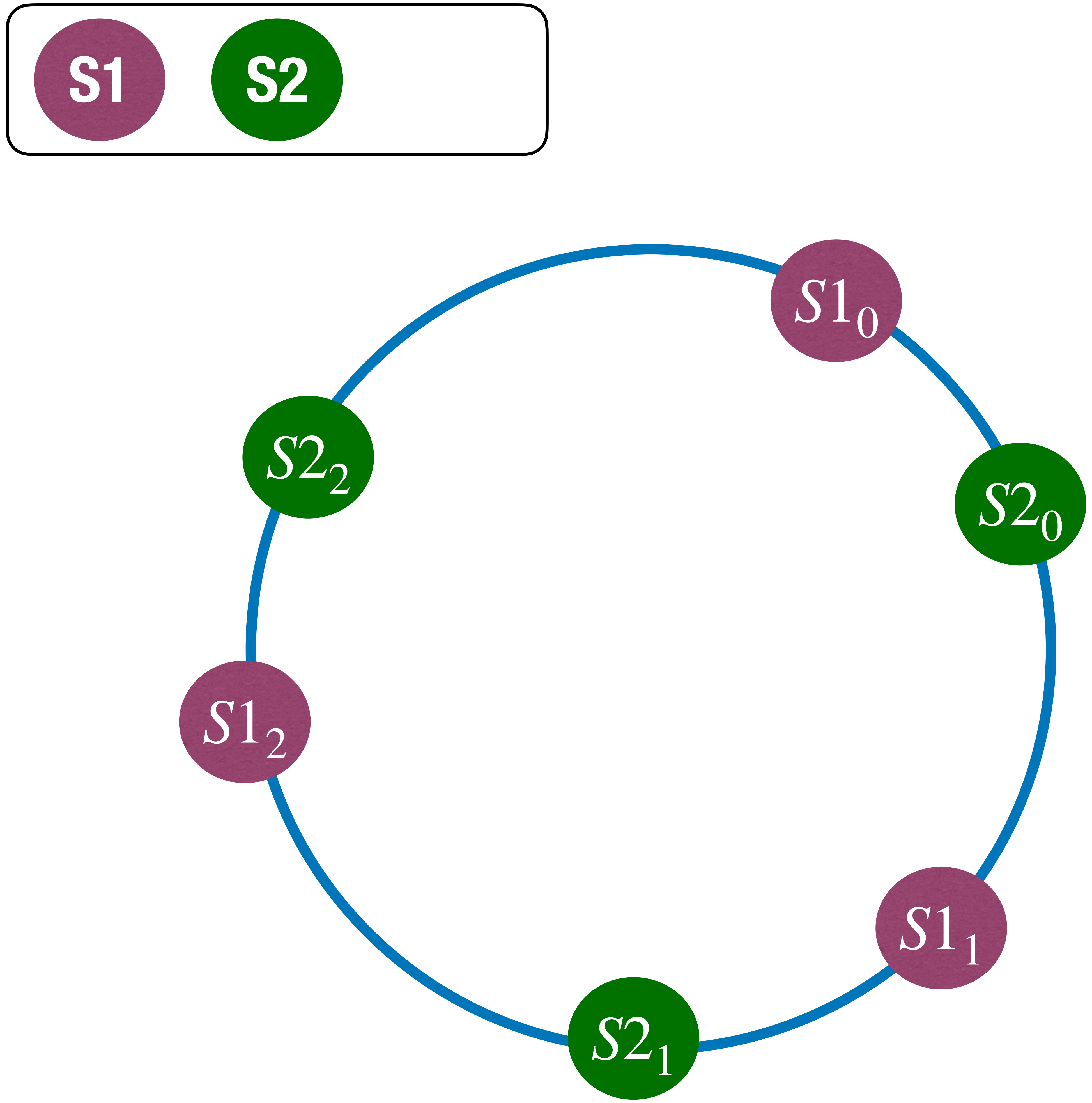

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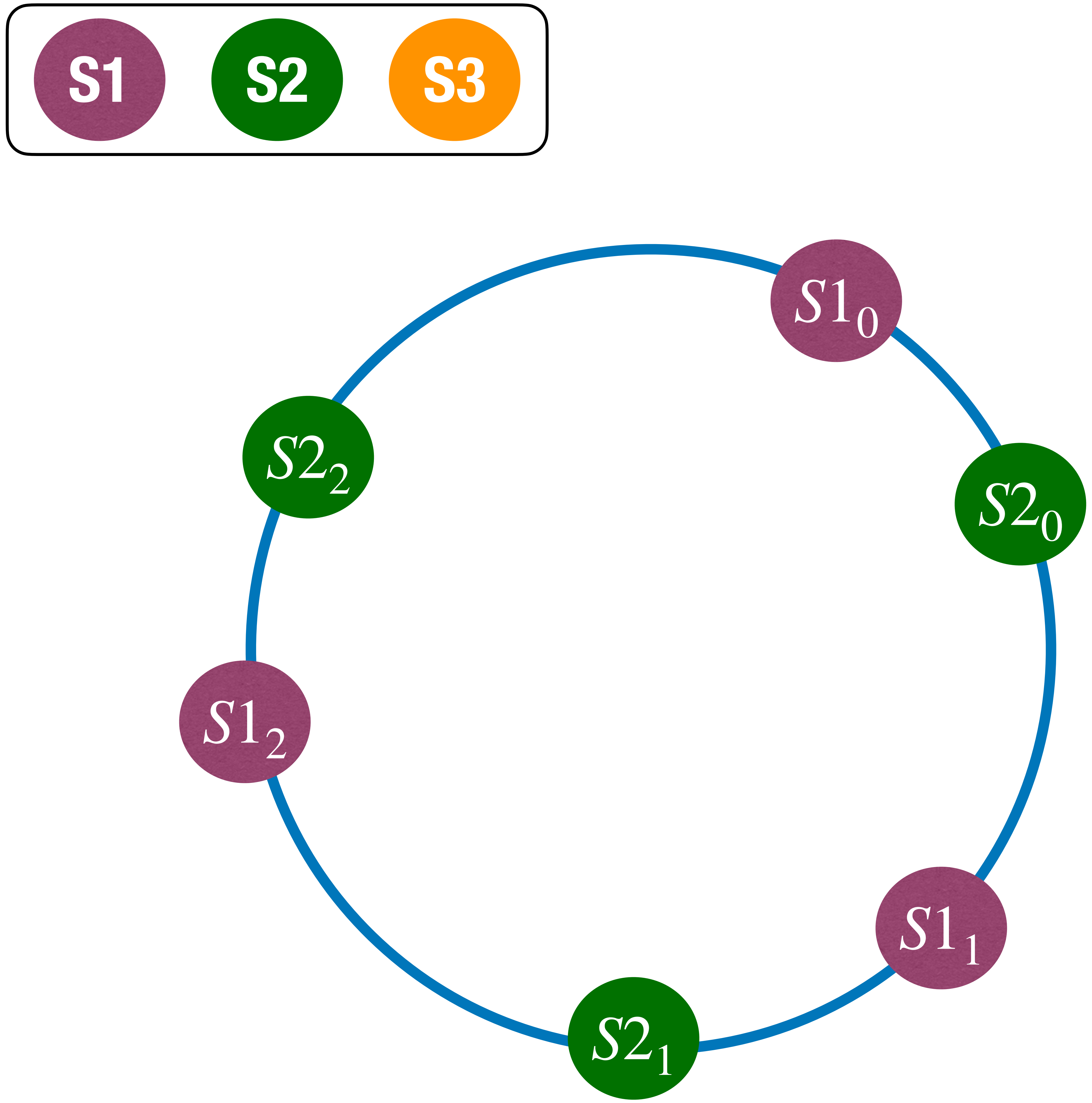

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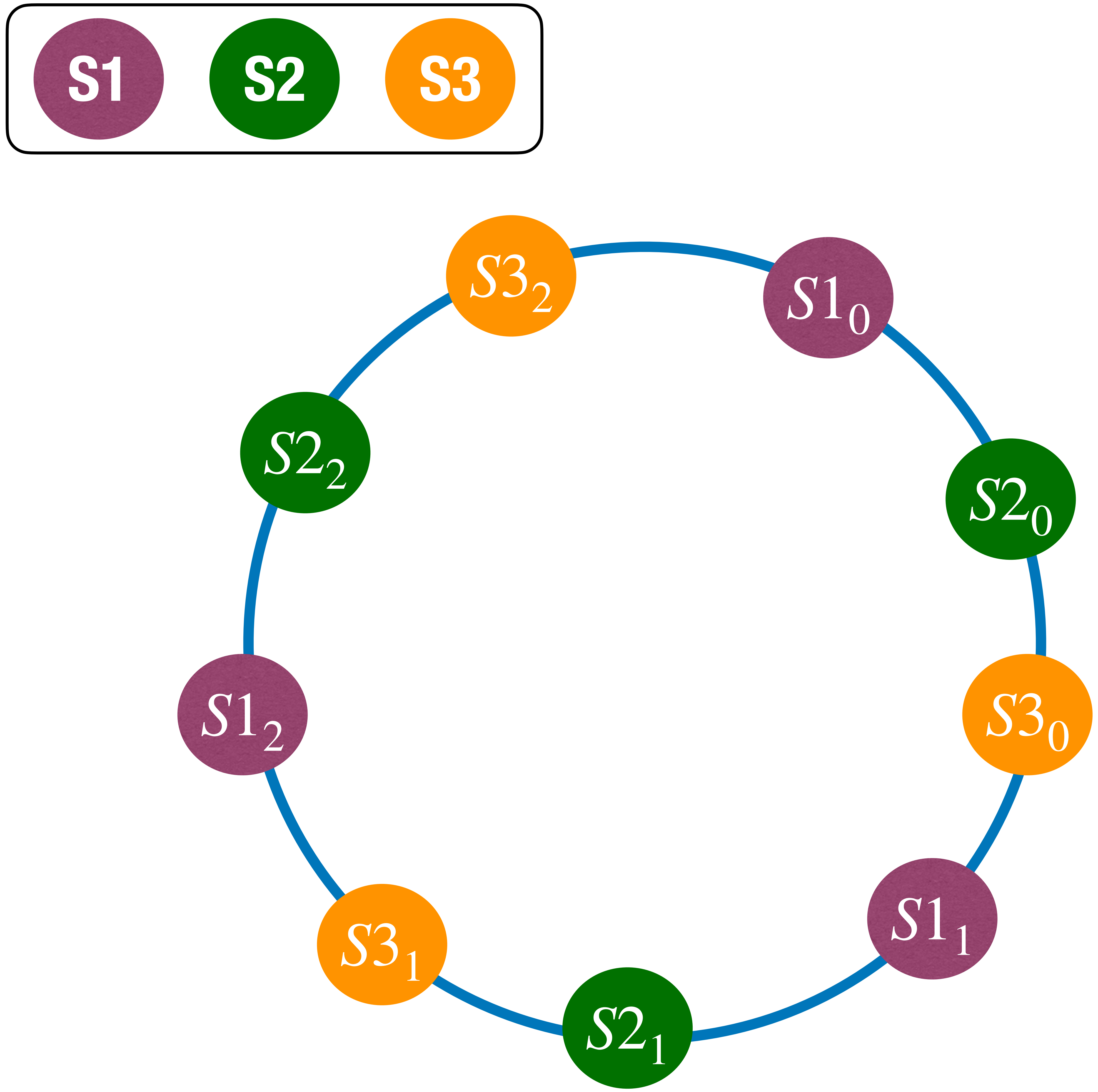

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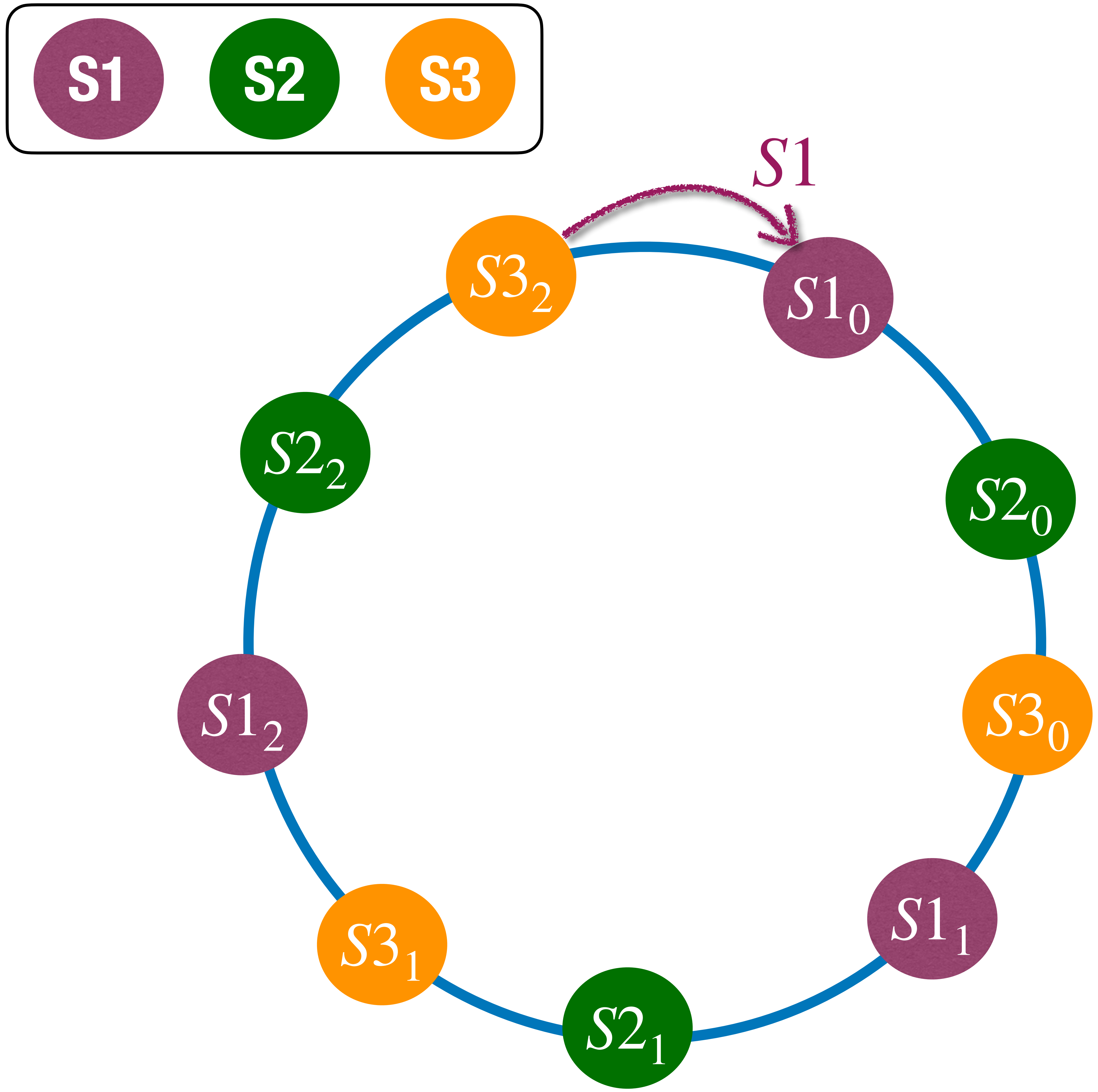

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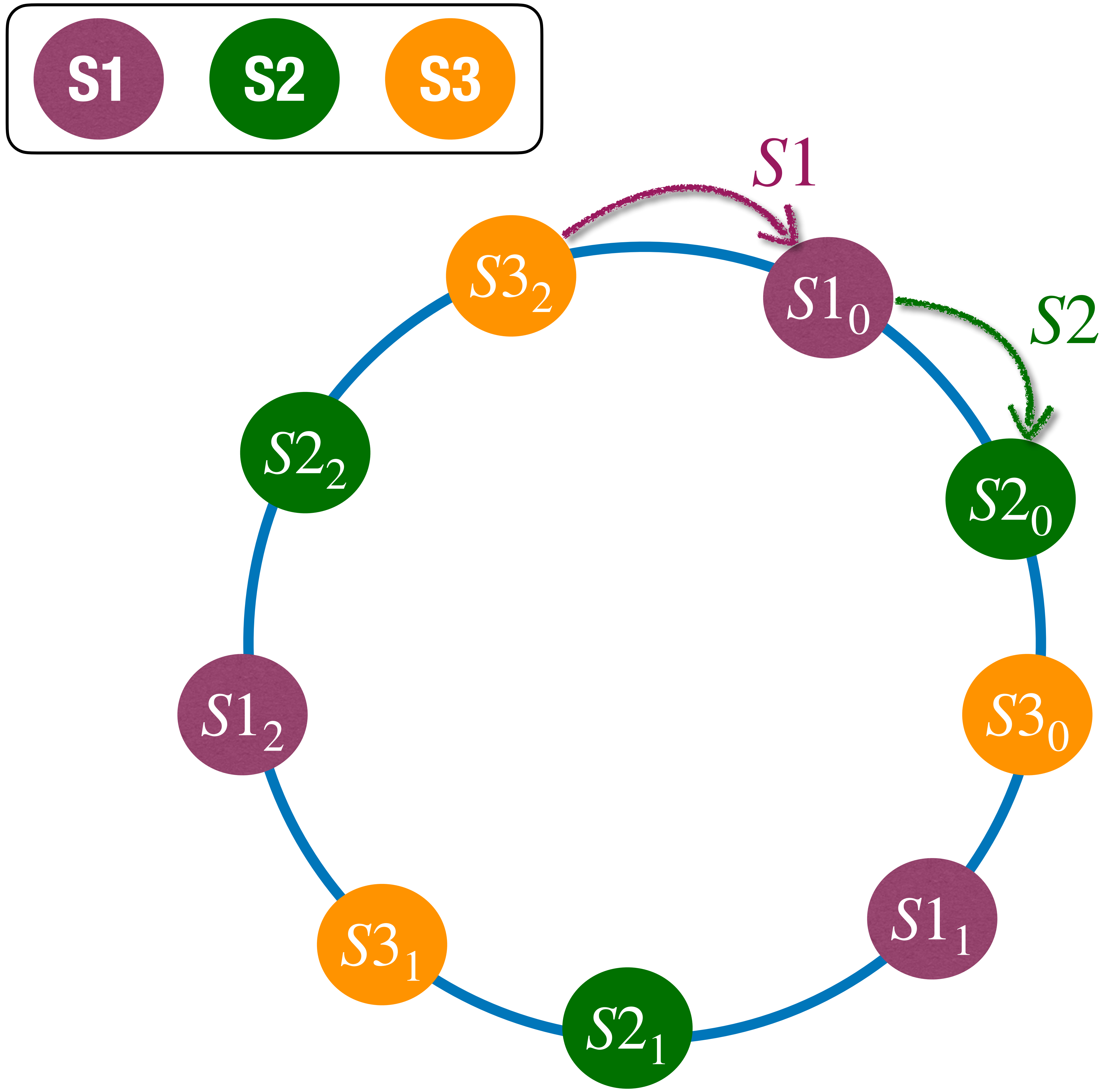

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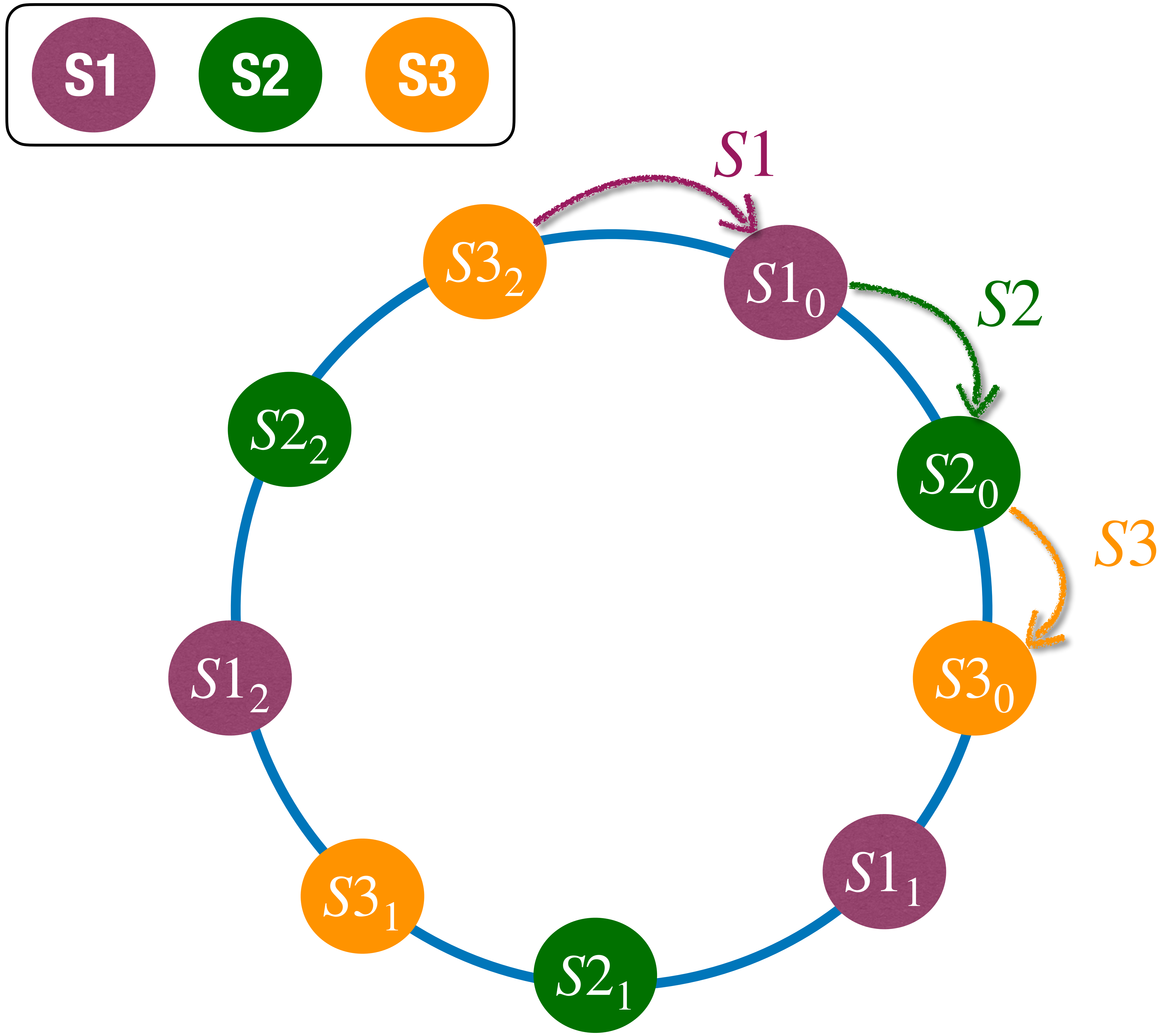

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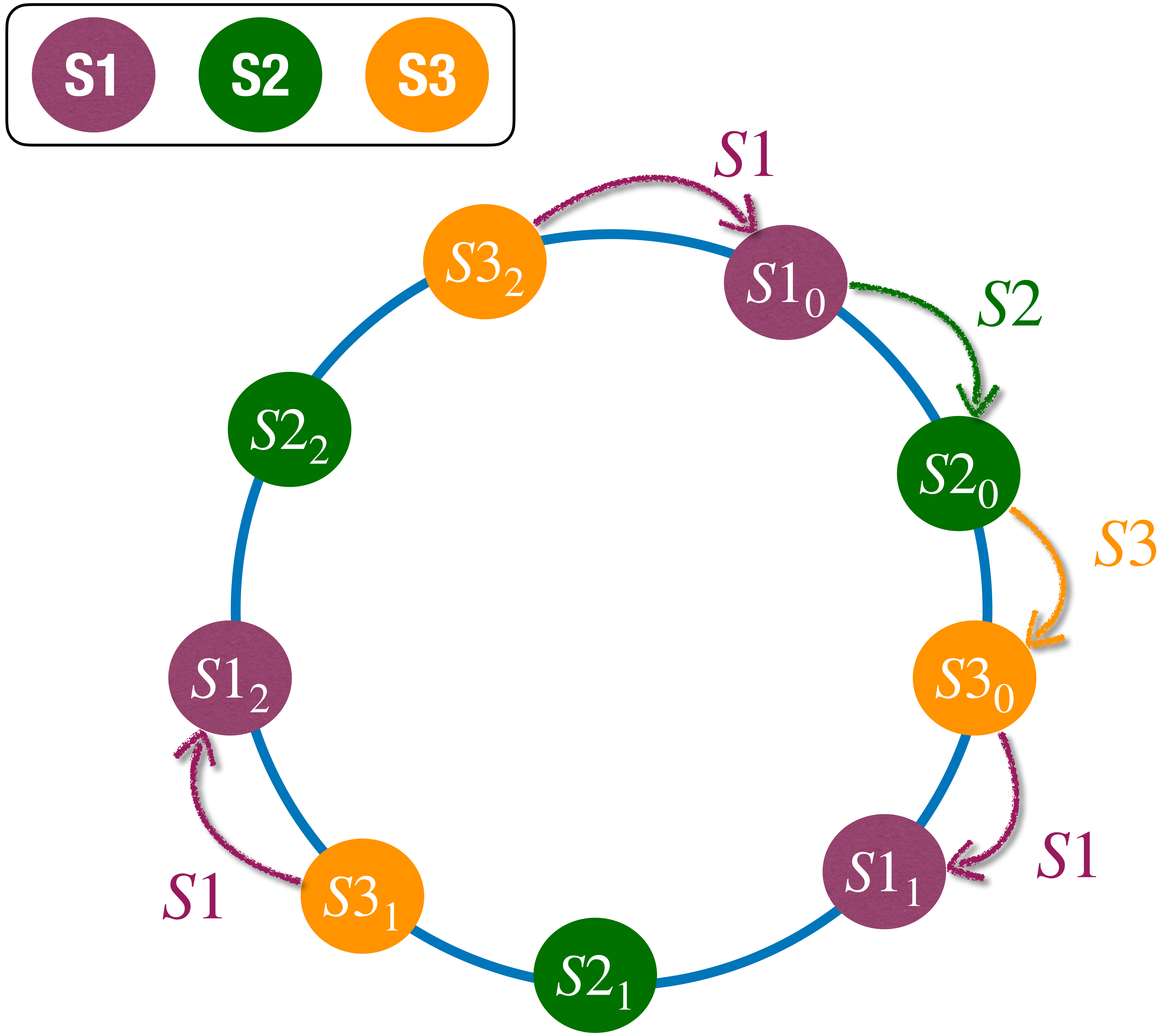

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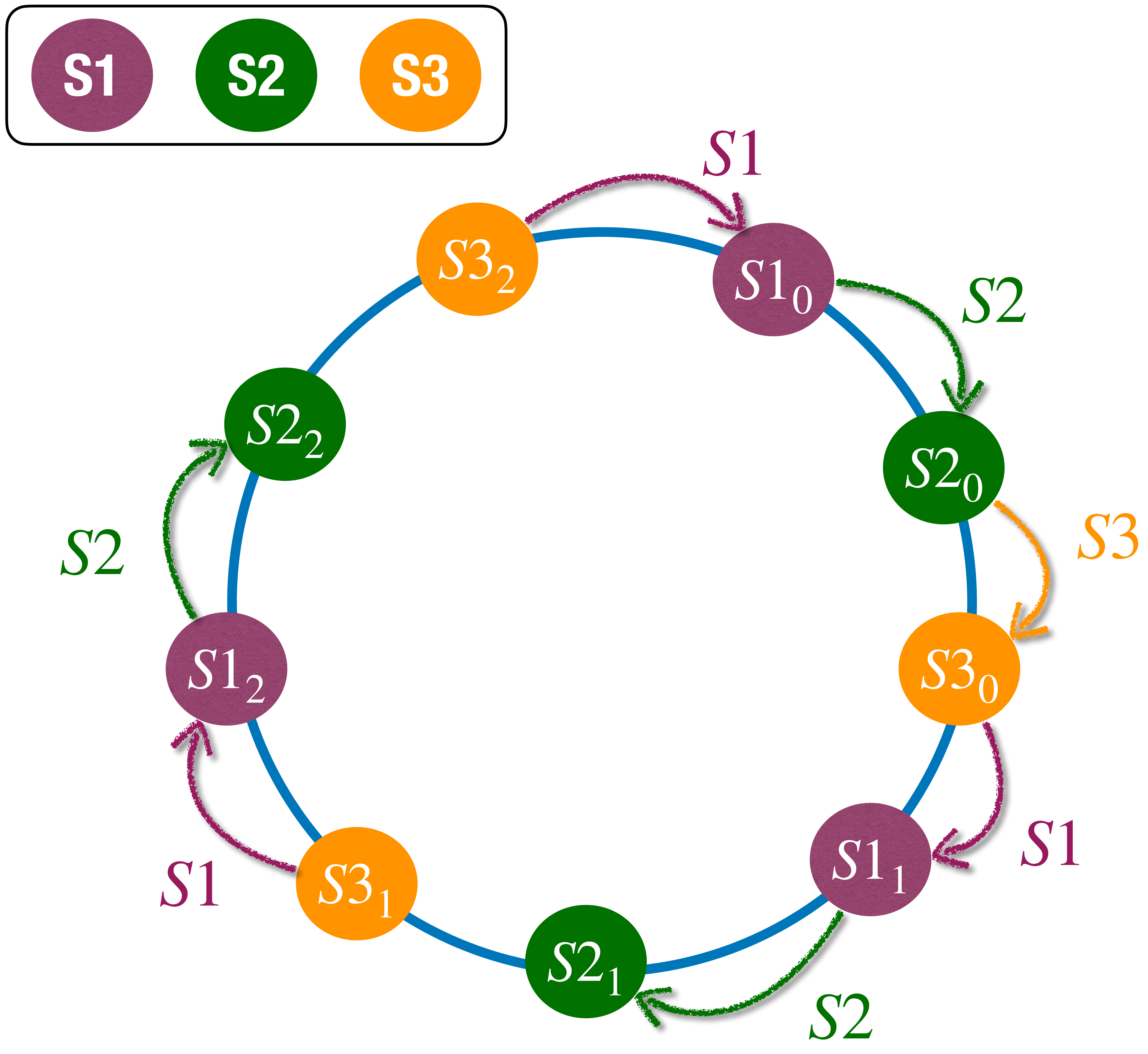

Similarly, adding virtual nodes to hash ring

- Virtual nodes (vnodes) are multiple logical positions on the hash ring that map to the same physical server.
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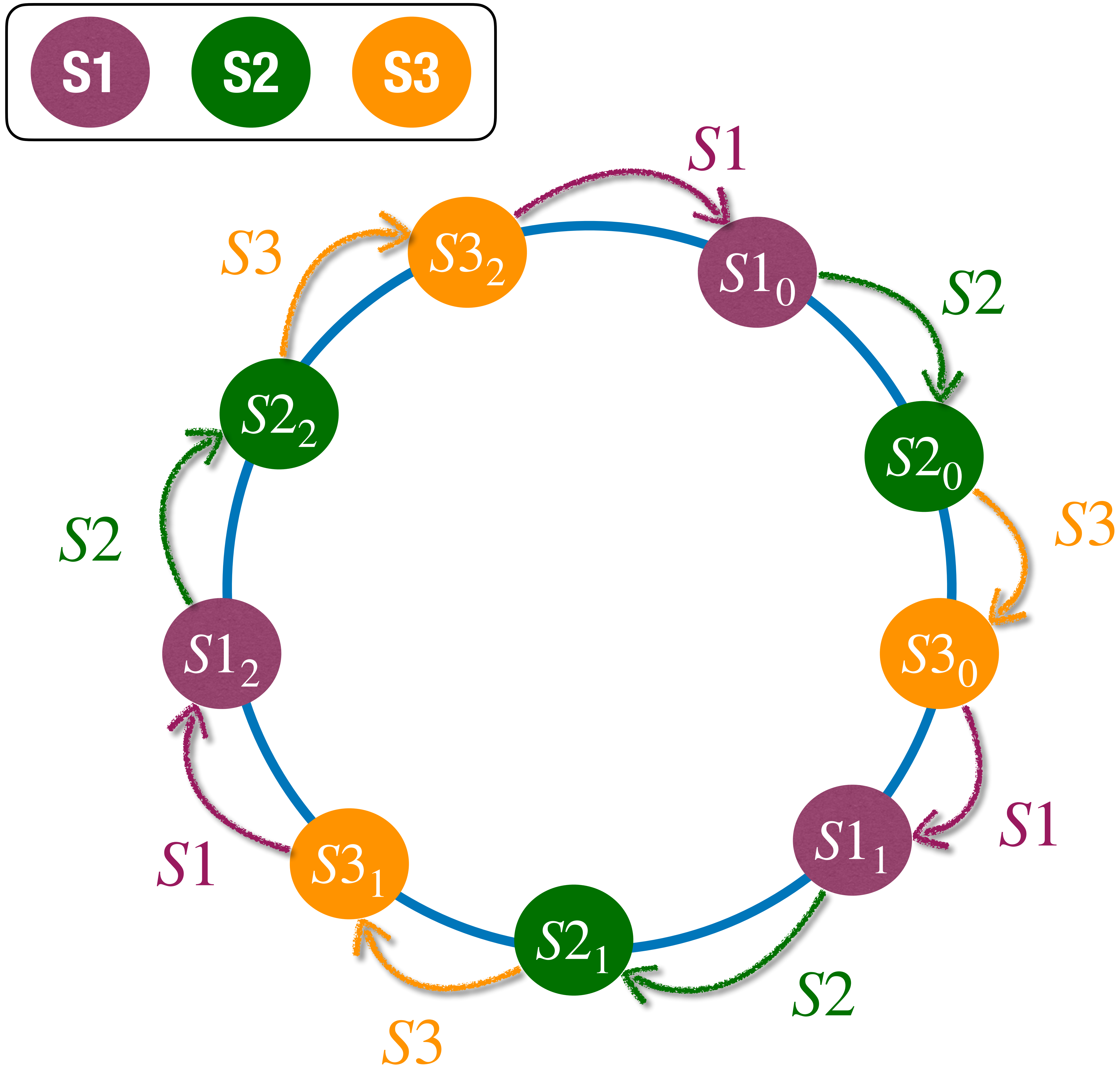

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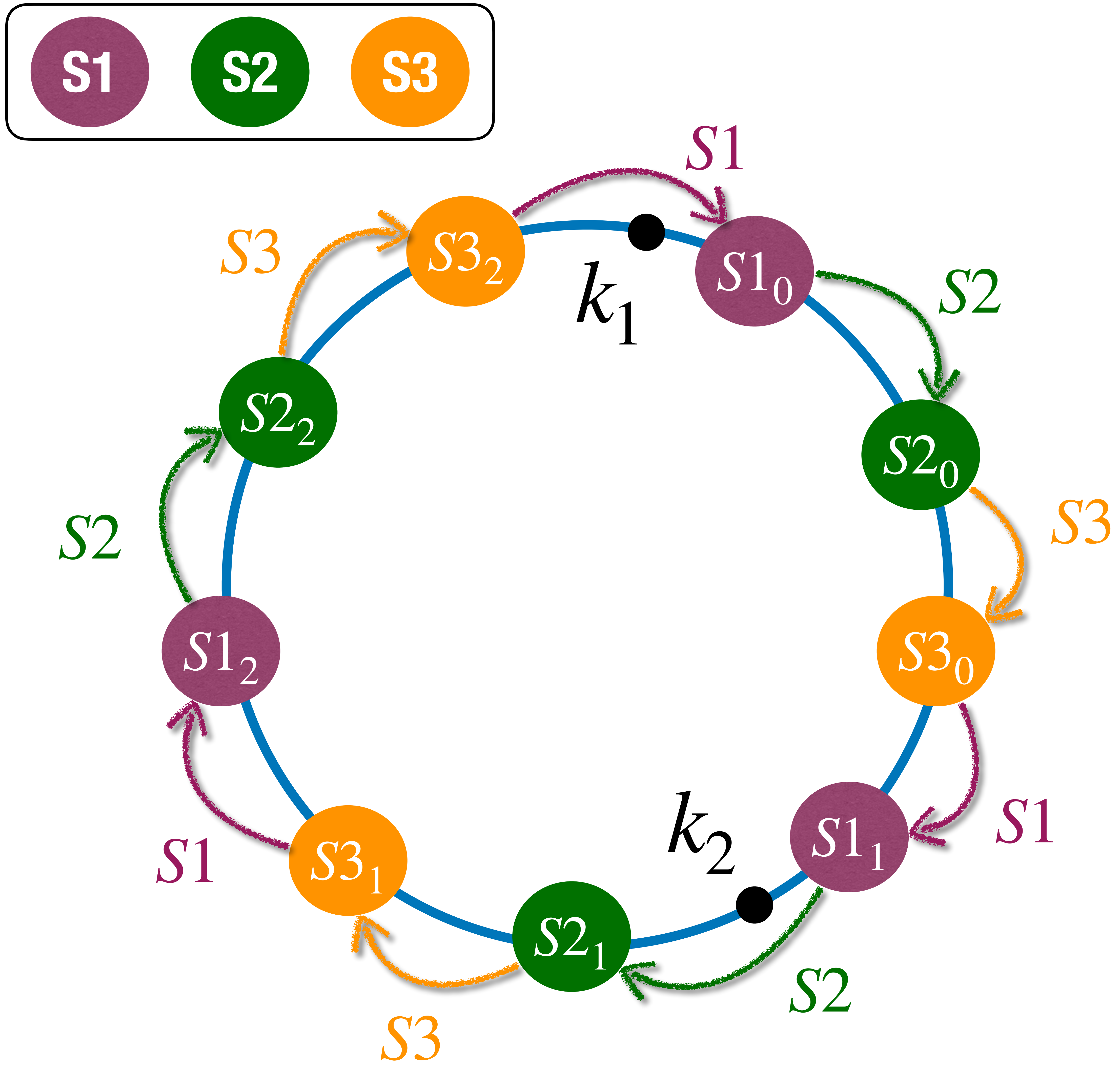

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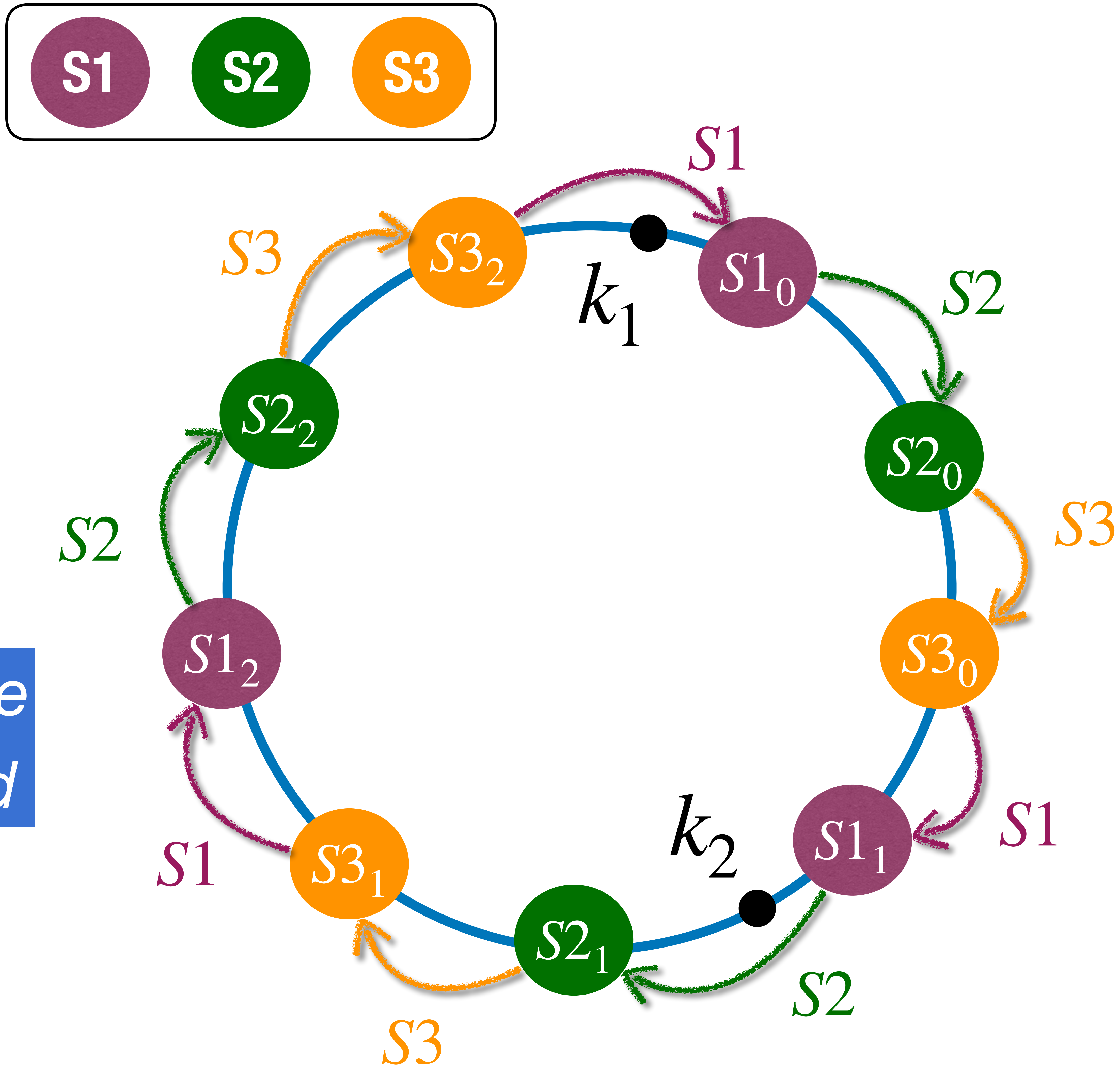

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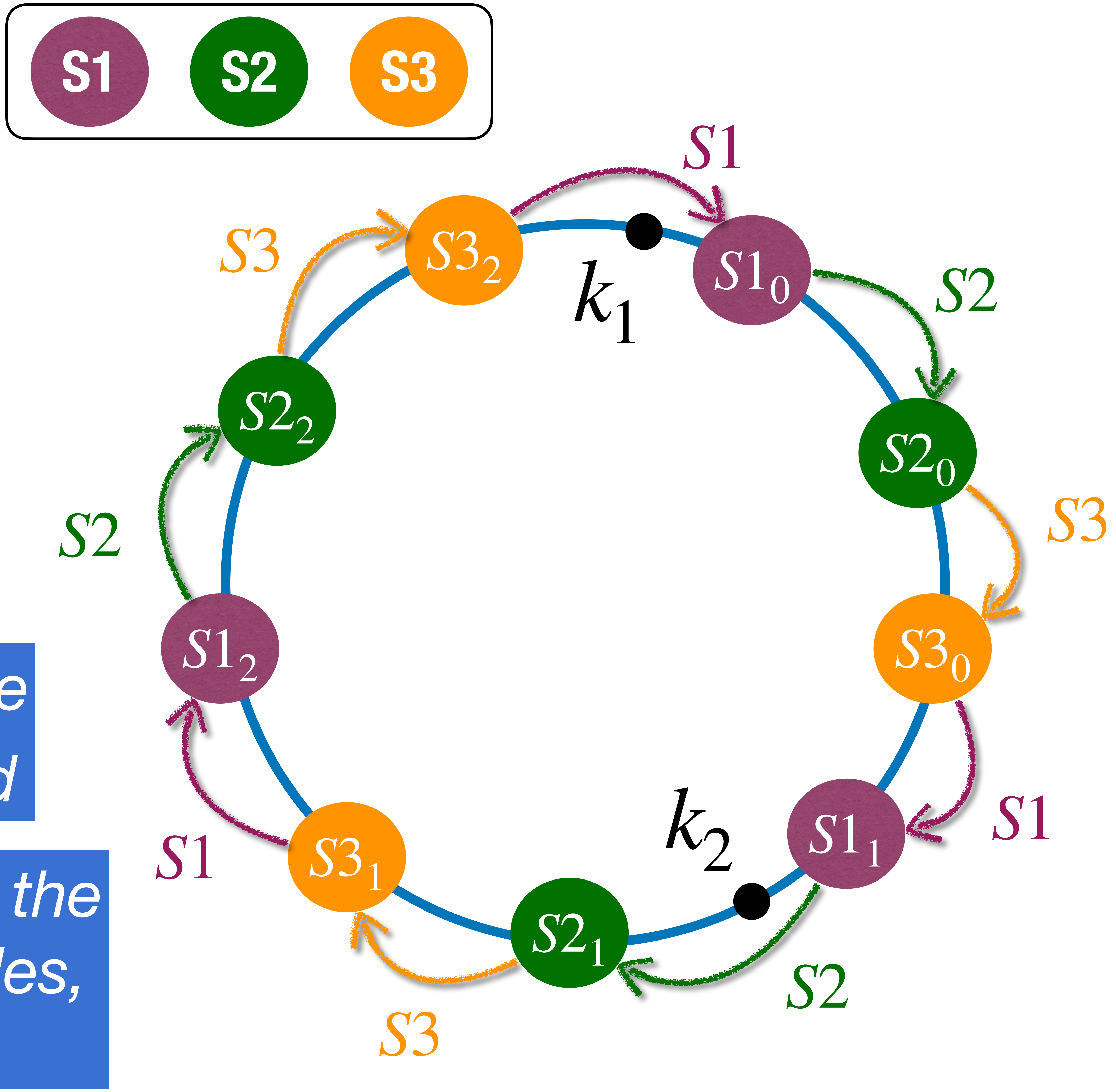
Support heterogeneous servers by adjusting the size of range. E.g., strong servers: 200 Vnodes, weak servers 50 Vnodes



Summary of consistent hashing

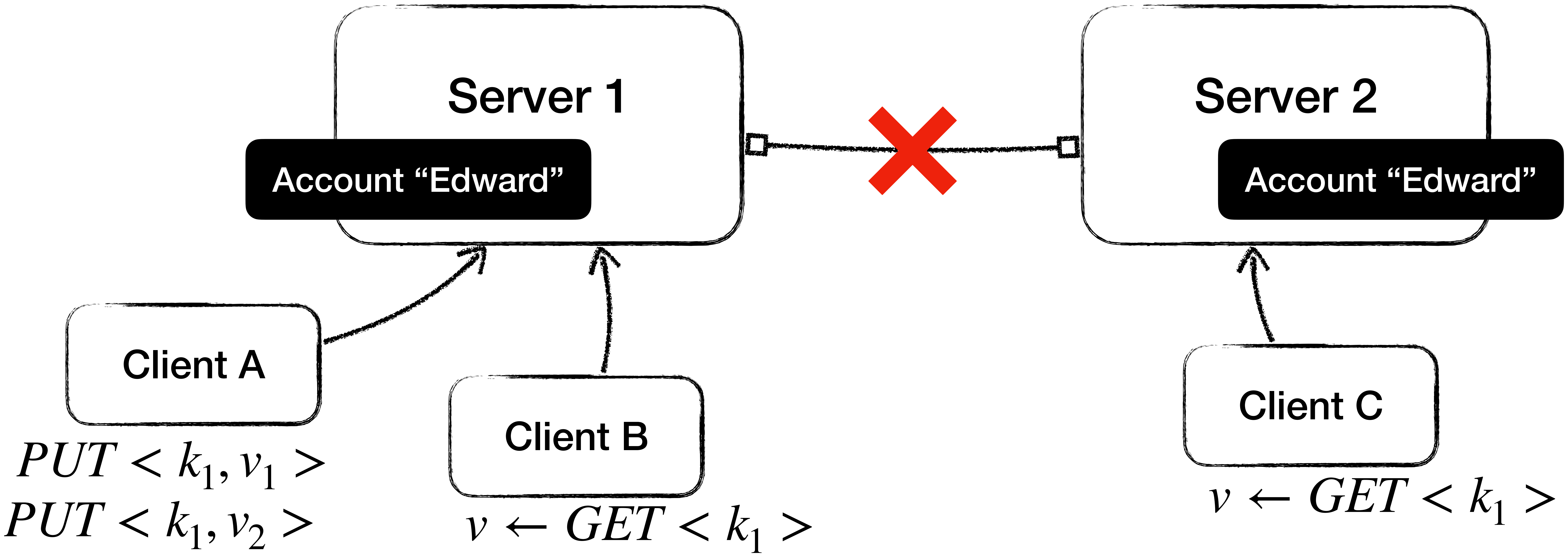
- Maps keys and servers into the same circular hash space (ring)
- Each key assigned to the next clockwise server
- When a server joins/leaves, only ≈ 1/N keys move
- Avoids global reshuffling required by naïve hashing
- Enables elastic scaling and graceful failure handling
- Uses virtual nodes to improve load balance and support heterogeneous servers

Today’s outline

Consistent Hashing

CAP

A simple network partition



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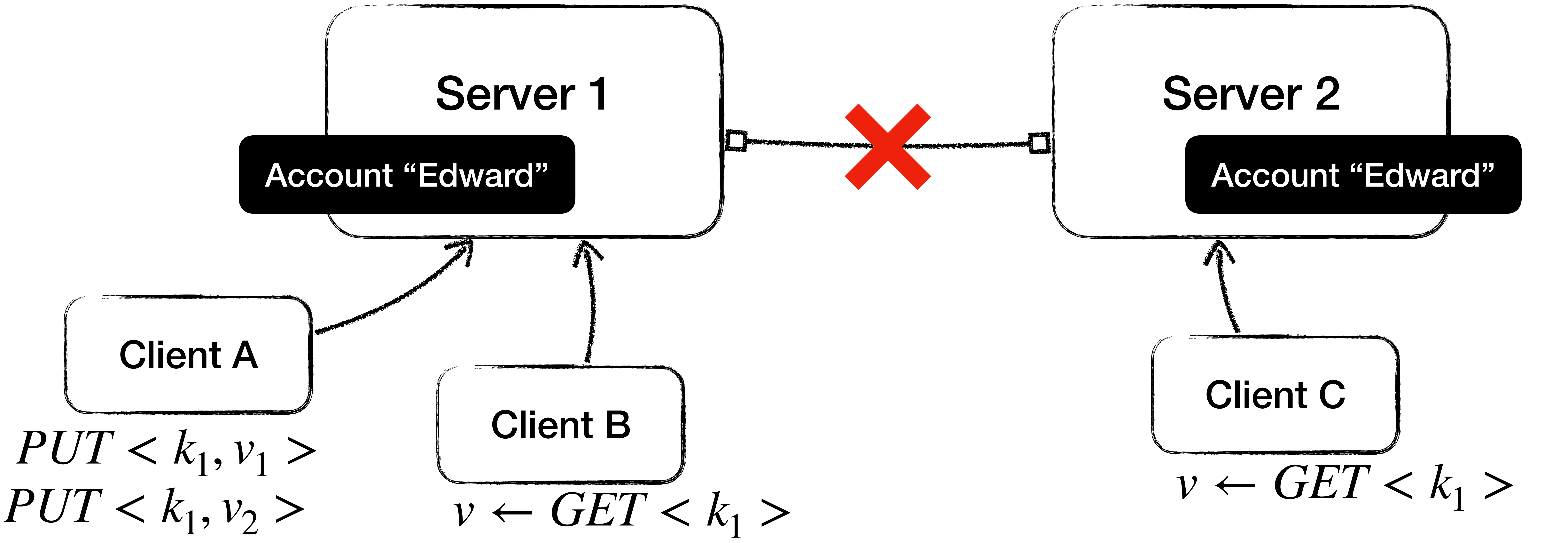

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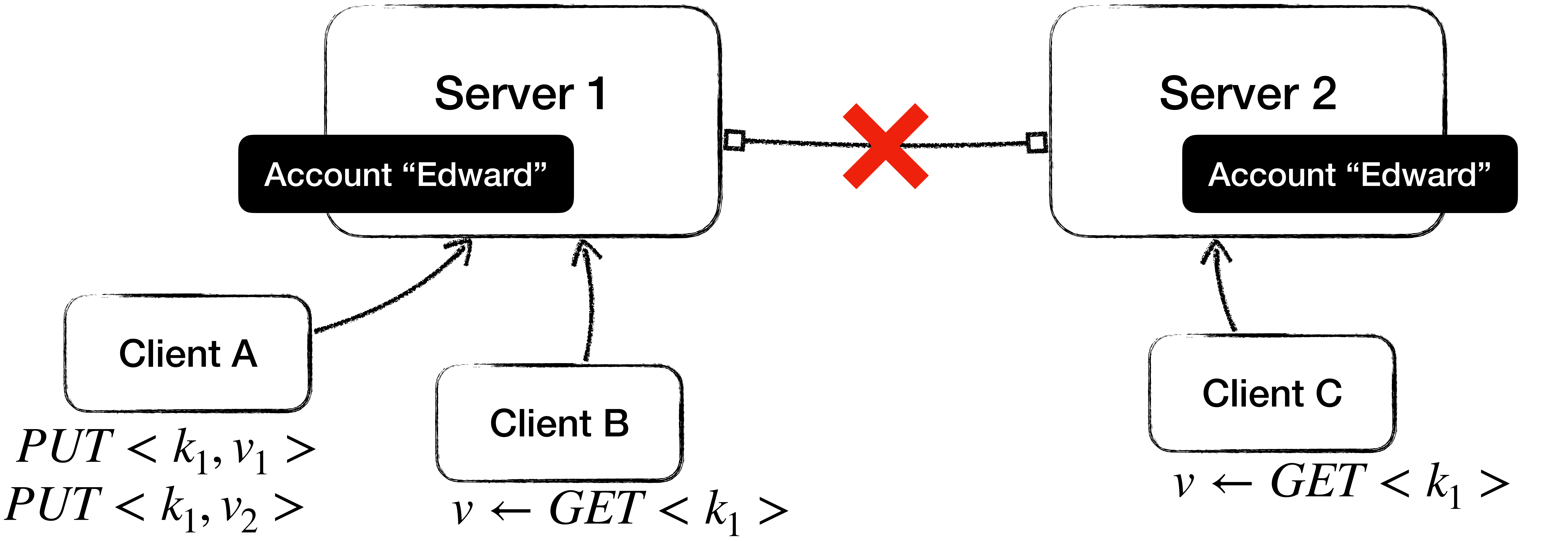

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Consistency > Availability

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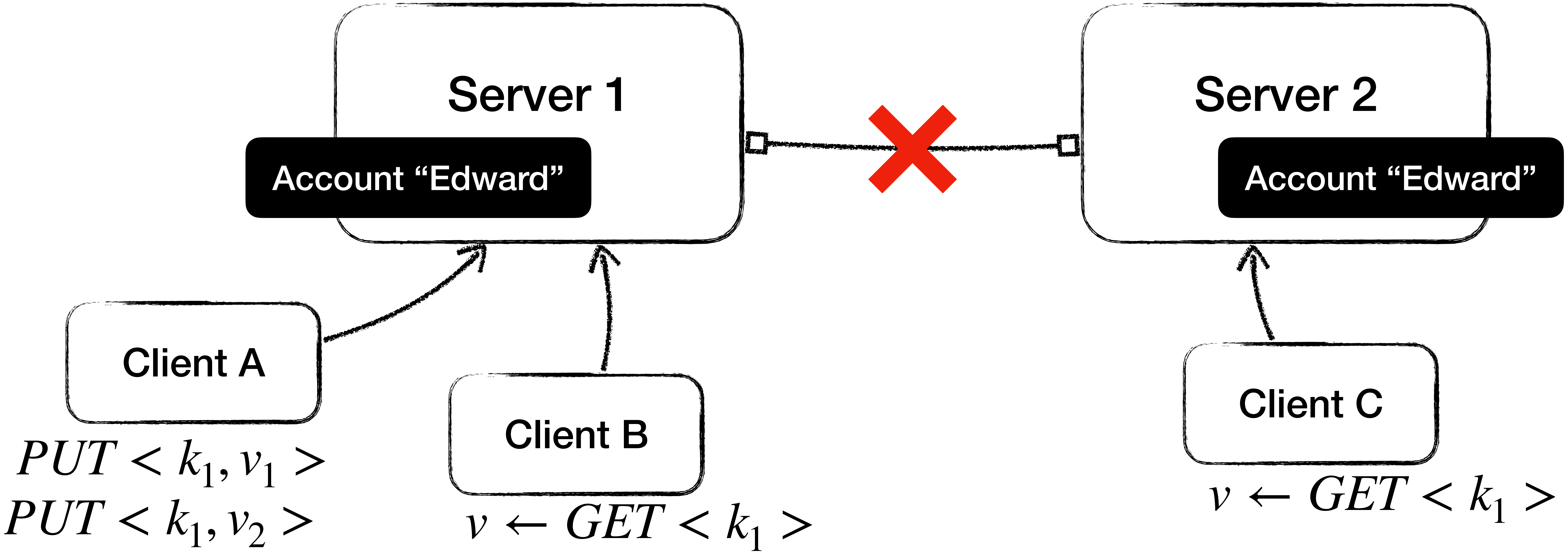

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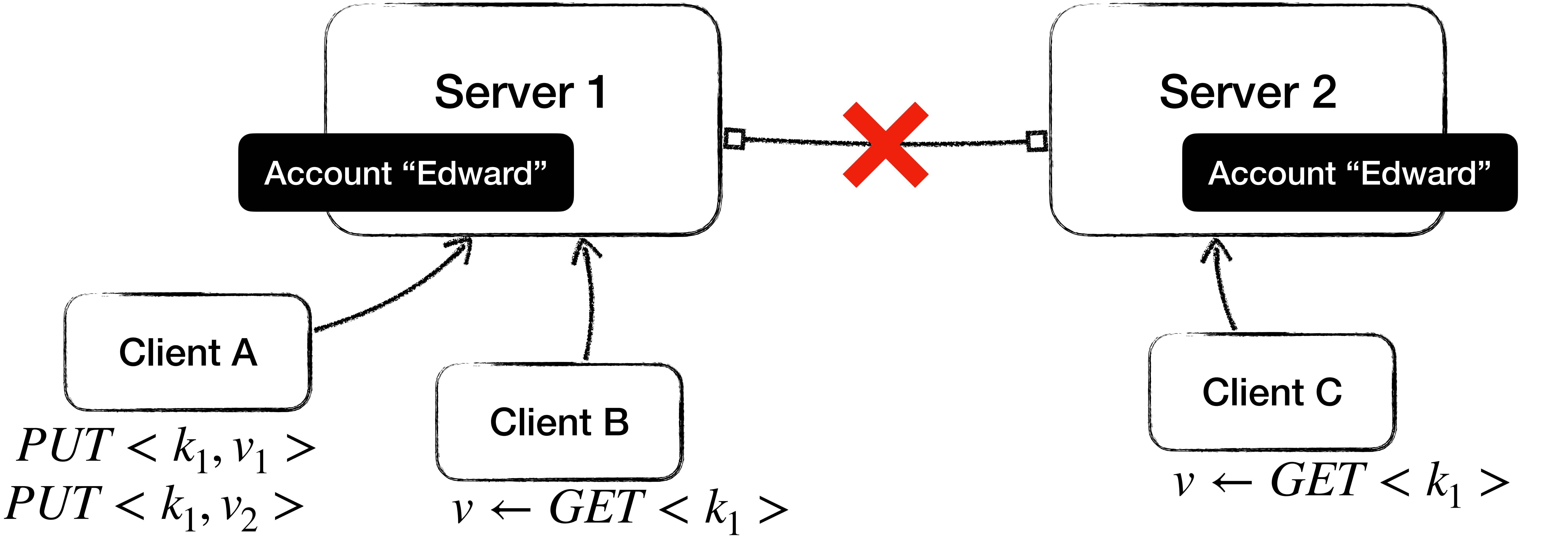

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Consistency > Availability

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Availability > Consistency

The CAP theorem

- It is **impossible** for a replicated **read-write store** in an asynchronous network to maintain the following **three guarantees simultaneously**:
    - Consistency
    - Availability
    - Partition-Tolerance
- Initially, conjectured by Eric Brewer in 1998, later proven by Lynch et al.
- Describes **tradeoffs** involved in distributed system design

CAP

- **Consistency:**
  - All read requests should read the latest value (or return an error)
- **Availability:**
  - All requests should return successfully
- **Partition-tolerance:**
  - The system can tolerate arbitrary number of communication failures
- Traditional view
  - Today, more a spectrum

Definition of Consistency

- Refers to replication consistency
  - Not related to A-C-I-D properties for transactions
- Ideally means strict consistency
  - As we know, this is by and large impossible in a distributed system
- Thus, here, assumes linearizability
- This usually means replication across sites should be done eagerly

Definition of Availability

- Every request received by a non-failed node must result in a non-error response
    - Non-triviality requirement: a system which always responds with errors is not available
- Assumes a crash failure model for nodes
    - Functioning nodes must continue to operate even if there are failed nodes in system
- No requirement on latency: response can be very slow but must eventually come through
- Both a weak and strong definition: no latency guarantee, but 100% response success

Definition of Partition-Tolerance

- Asynchronous system model
- Message loss (failure model)
- Partition means total communication loss between partitioned subsystems
- System continues request processing even if a network partition causes communication loss between subsystems
- If the system requires a stronger system model, or a weaker failure model, then it is not partition-tolerant
- No guarantee that partitions recover, but it doesn’t mean they are always present either

Common misunderstanding in CAP

- CAP does NOT say:
    - You can only pick two and permanently give up the third
- It says:
    - When a partition happens, you must choose between C and A

CP vs AP

- In advanced distributed systems (e.g., blockchains, cloud DBMS):
  - CP systems often use consensus (e.g., Paxos, Raft)
  - AP systems often use eventual consistency

- Many practical systems allow tuning:
  - MongoDB has configurable consistency
  - Cassandra has unable quorum reads/writes

Worksheet