Reliable Systems

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Learning Goals

- Learn how to keep a system running when nodes fail.
- Understand trade offs between consistency and availability.

Situation

Your system is horizontally scaled with nodes arranged in a **ring using consistent hashing**. Load is managed with horizontal scaling, consistent hashing and a network load balancer.

Problem: Roughly once every three months, a server may fail, causing downtime for reads and writes.
Goal: Design a system that remains fully available, allowing reads and writes even when a single node goes down.

Deliverables

System Design

Design a system that allows a node to temporarily go down while still giving read and write access to your data with zero downtime. Draw pictures and explain how it works.

Considerations

To help focus your design, consider: - How might you replicate data across multiple nodes?
- How will clients continue to access data if a node fails?
- What consistency and availability trade offs should you consider?
- How might your design affect read/write latency under node failure?
- How should the system handle nodes rejoining after a failure?
- How does your design scale as the system grows in nodes or data volume?

Reference Solution: Reliable Systems

System Design

- **Topology**
  - **Consistent hashing ring** with virtual nodes to smooth key distribution.
  - **Replication factor N=3**: each key is stored on its primary and the next two successors on the ring.
- **Client routing**
  - Clients use a **stateless load balancer** to hit any healthy node.
  - Each node can act as a **coordinator**: computes a key's replica set from ring membership and forwards to replicas.
- **Writes**
  - **Tunable consistency** with quorum: require W replicas to ack before success.
  - Choose defaults W=2, R=2 with N=3 so R+W>N for overlap.

- If a replica is down, use **sloppy quorum**: write to next healthy nodes and store **hints** for original owners.
- **Durability:** append to a commit log before ack; then apply to storage (e.g., LSM-tree/B-Tree).

- **Reads**
  - Coordinator queries R replicas.
  - Return the newest version via **timestamps** or **vector clocks**; apply **read repair** in background when replicas diverge.

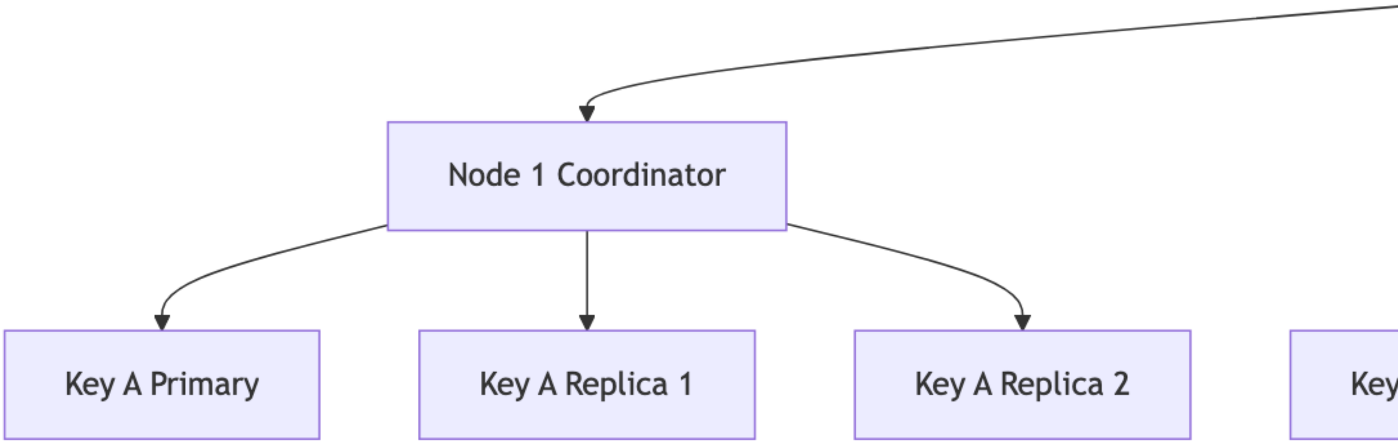
- **Failure detection**
  - **Gossip protocol** for membership; phi-accrual/heartbeat for suspicion and timing.

- **Recovery**
  - On rejoin, peers deliver **hinted handoff** data.
  - Run **anti-entropy** synchronization (e.g., Merkle trees) to reconcile ranges.

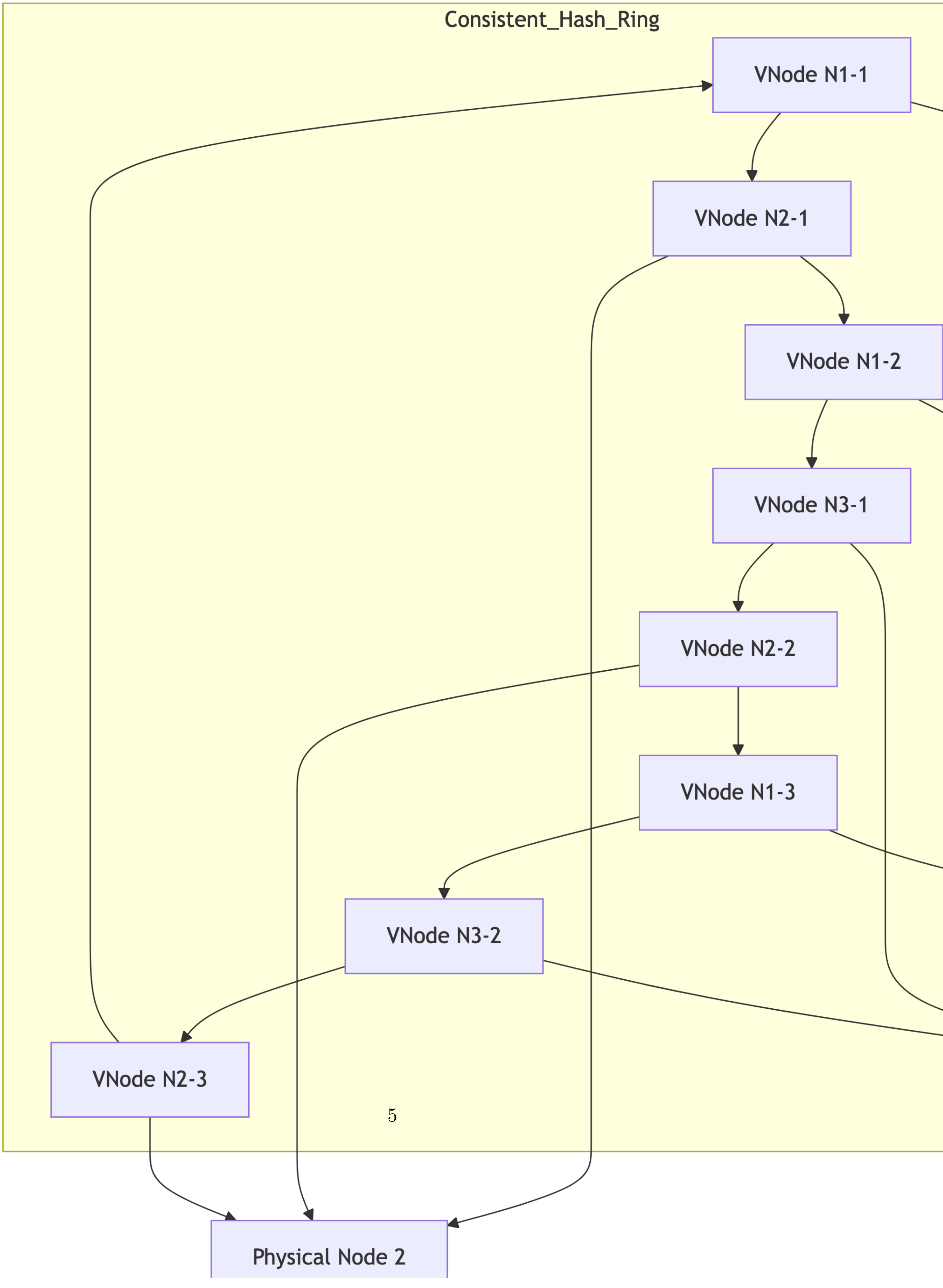
- **Operations**
  - **Rebalancing:** consistent hashing + vnodes limit key movement when scaling.
  - **Backpressure:** protect nodes with queue limits and admission control.

Diagrams

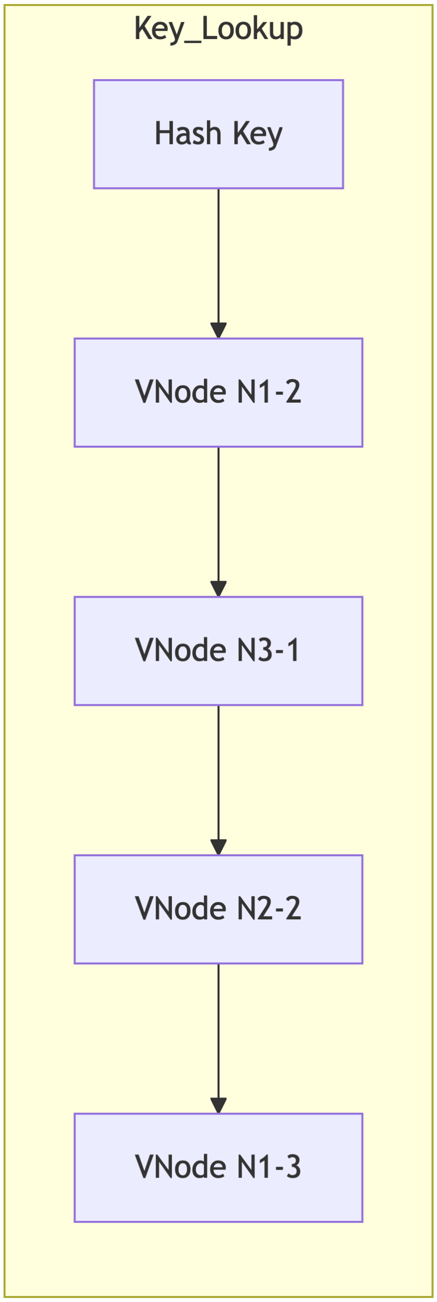
1. System Architecture



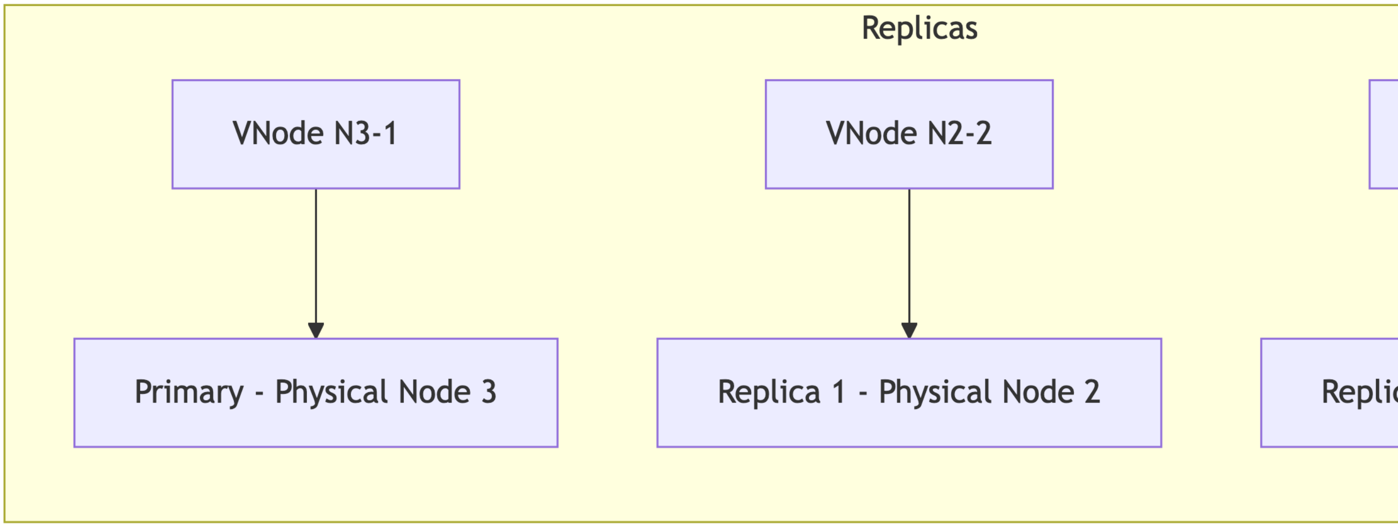
2. Consistent Hash Ring with Virtual Nodes


Consistent_Hash_Ring
VNode N1-1
VNode N2-1
VNode N1-2
VNode N3-1
VNode N2-2
VNode N1-3
VNode N3-2
VNode N2-3
Physical Node 2

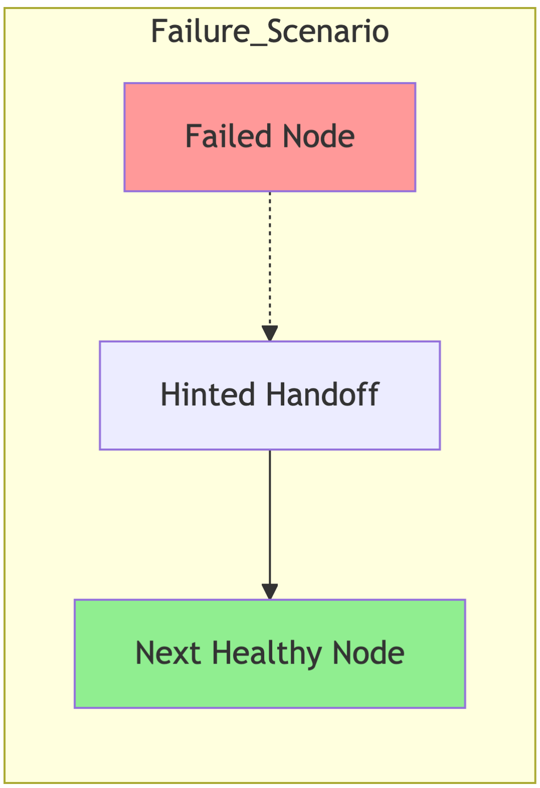
3. Key Lookup Process



4. Replica Assignment



5. **Failure Handling**



How Virtual Nodes Work

With virtual nodes, each physical node is mapped to multiple positions on the hash ring:

1. **Each physical node creates multiple vnodes** by hashing its identifier with different indices
2. **Vnodes are placed on the ring** at positions determined by their hash values
3. **Keys are assigned to the next vnode** in clockwise order from the key's hash position
4. **Replication follows the ring** - the next N vnodes after a key's primary vnode store its replicas

Finding consecutive nodes with vnodes: - Hash the key to find its position on the ring - Walk clockwise to find the next N vnodes - Map each vnode back to its physical node - If multiple vnodes belong to the same physical node, skip to the next unique physical node - Continue until you have N distinct physical nodes

This approach ensures better load distribution and makes scaling more efficient since only a fraction of keys need to be remapped when nodes are added or removed.

Considerations

- **Replication across nodes**
  - Replicate to N=3 consecutive nodes; use vnodes to avoid hot spots and ease rebalancing.
- **Access during node failure**
  - Coordinator writes to any W healthy replicas via sloppy quorum.
  - Reads succeed from any R healthy replicas; stale replicas get repaired.
- **Consistency vs availability**
  - Prefer availability with tunable consistency (AP); allow per-request overrides.
  - Pick R,W such that R+W>N for read-write overlap when needed.
- **Latency under failure**
  - Quorum waits and alternate replica routing can add tail latency.
  - Mitigate with hedged requests and sensible timeouts.
- **Node rejoin handling**
  - Hinted handoff delivers missed writes; anti-entropy ensures full reconciliation.
  - Gradually restore traffic to rejoined nodes.
- **Scalability**
  - Add nodes horizontally; only local ranges move due to consistent hashing.
  - Place replicas across racks/AZs to isolate failure domains.

Recommended Actions

- [**replication**] Set N=3 with rack/AZ-aware placement.
- [**consistency**] Default R=2, W=2; support per-request overrides.
- [**availability**] Implement sloppy quorum and hinted handoff.
- [**repair**] Add read repair and periodic Merkle-tree anti-entropy.
- [**membership**] Use gossip and a phi-accrual failure detector.
- [**operability**] Track quorum latency, hint queues, and read-repair rate.