Consistent Hashing - 1 Hour Session

Duration: 60 minutes **Level:** Intermediate

📋 Session Agenda

- [ ] Introduction to Consistent Hashing (10 min)
- [ ] Hash Ring Fundamentals (15 min)
- [ ] Virtual Nodes (10 min)
- [ ] Rebalancing & Data Migration (10 min)
- [ ] Implementation & Real-World Applications (15 min)

🎯 Learning Objectives

By the end of this session, you will understand: - Why traditional hashing fails in distributed systems - How consistent hashing solves the redistribution problem - The hash ring concept and key placement - Virtual nodes and their benefits - How to handle node additions and removals - Real-world applications in distributed databases and caches

1. Introduction to Consistent Hashing (10 min)

The Problem with Traditional Hashing

Simple Modulo Hashing:

```
server_index = hash(key) % number_of_servers

Example with 4 servers:
hash("user:123") = 12345
server = 12345 % 4 = 1  → Server 1
```

What happens when we add/remove a server?

```
Before: 4 servers
hash("user:123") % 4 = 1  → Server 1
hash("user:456") % 4 = 0  → Server 0
hash("user:789") % 4 = 3  → Server 3

After: 5 servers (added one)
hash("user:123") % 5 = 0  → Server 0 (MOVED!)
hash("user:456") % 5 = 0  → Server 0 (same)
hash("user:789") % 5 = 4  → Server 4 (MOVED!)

Result: ~80% of keys need to be remapped! 💥
```

> ⚠️ **Warning** With N servers, adding or removing one server causes (N-1)/N keys to be remapped. For 100 servers, that’ s 99% of all data!

Why This Matters

Impact on Distributed Systems: - 🔥 **Cache Invalidation:** Massive cache misses during scaling - 📊 **Database Sharding:** Expensive data migration - ⏱️ **Downtime:** System unavailable during rebalancing - 💰 **Cost:** Network bandwidth and compute for data movement

The Solution: Consistent Hashing

Key Insight: Instead of mapping keys to servers directly, map both keys AND servers to a fixed hash space (ring).

```
Traditional:   key → hash → server_index
Consistent:    key → hash → position_on_ring → nearest_server
```

Benefits: - Only K/N keys remapped when adding/removing nodes (K = total keys, N = nodes) - Minimal data movement during scaling - Predictable load distribution

2. Hash Ring Fundamentals (15 min)

The Hash Ring Concept

Creating the Ring:

```
Hash Space: 0 to 2^32 - 1 (or any large number)
Visualized as a circle (ring)

        0
        │
   270° ┼ 90°
        │
      180°

Position = hash(identifier) % ring_size
```

Placing Servers on the Ring

```python
import hashlib

def hash_to_ring(key, ring_size=2**32):
    """Hash a key to a position on the ring"""
    hash_value = int(hashlib.md5(key.encode()).hexdigest(), 16)
    return hash_value % ring_size

# Place servers on the ring
servers = ["server-A", "server-B", "server-C", "server-D"]
server_positions = {s: hash_to_ring(s) for s in servers}

# Example positions (simplified to 0-360 for visualization)
# server-A: 45°
# server-B: 120°
# server-C: 200°
# server-D: 300°
```

Visual Representation:

```
           0°
           |
           |    server-A (45°)
           |   /
          /|\
         / | \
server-D  |  \
 (300°)   |   server-B (120°)
        \ |  /
         \| /
          |
          |
     server-C (200°)
```

Key Placement: Finding the Right Server

Rule: A key is assigned to the first server encountered when moving clockwise from the key’s position.

```
    def find_server(key, server_positions):
        """Find the server responsible for a key"""
        key_position = hash_to_ring(key)

        # Sort servers by position
        sorted_servers = sorted(server_positions.items(), key=lambda x: x[1])

        # Find first server clockwise from key position
        for server, position in sorted_servers:
            if position >= key_position:
                return server

        # Wrap around to first server
        return sorted_servers[0][0]
```

Example:

```
Key "user:123" hashes to position 80°

Ring positions:
- server-A: 45°
- server-B: 120°  ← First server clockwise from 80°
- server-C: 200°
- server-D: 300°

Result: "user:123" → server-B
```

Adding a New Server

```
Before: 4 servers
                    0°
                    |
                    |    A (45°)
                   /|\
                  / | \
              D   |   B (120°)
            (300°)|  /
                 \| /
                  |
              C (200°)

After: Add server-E at 150°
                    0°
                    |
                    |    A (45°)
                   /|\
                  / | \
              D   |   B (120°)
            (300°)|    \
                 \|     E (150°)  ← NEW
                  |    /
              C (200°)

Only keys between 120° and 150° move from C to E!
```

Impact Analysis:

```
        # Keys affected when adding server-E at 150°
        # Only keys in range (120°, 150°] move from server-C to server-E

        # Before: Keys 121°-200° → server-C
        # After:  Keys 121°-150° → server-E
        #         Keys 151°-200° → server-C

        # Percentage moved: (150-120)/(360) ≈ 8.3% of total keys
        # Much better than 80% with modulo hashing!
```

Removing a Server

```
Remove server-B (120°):

Before:
- Keys 46°-120° → server-B

After:
- Keys 46°-120° → server-E (next clockwise server)

Only server-B's keys need to move!
```

3. Virtual Nodes (10 min)

The Load Imbalance Problem

With few physical nodes, distribution can be uneven:

```
4 servers, random positions:
- server-A: 10°   (covers 10° of ring = 2.8%)
- server-B: 50°   (covers 40° of ring = 11.1%)
- server-C: 300°  (covers 250° of ring = 69.4%)
- server-D: 350°  (covers 50° of ring = 13.9%)

server-C handles 69% of all keys! 💥
```

Solution: Virtual Nodes (VNodes)

Idea: Each physical server gets multiple positions on the ring.

```python
def create_virtual_nodes(server, num_vnodes=150):
    """Create multiple positions for a single server"""
    vnodes = {}
    for i in range(num_vnodes):
        vnode_key = f"{server}#vnode{i}"
        position = hash_to_ring(vnode_key)
        vnodes[position] = server
    return vnodes

# Example: server-A with 3 virtual nodes
# server-A#vnode0 → position 45°
# server-A#vnode1 → position 180°
# server-A#vnode2 → position 290°
```

Visual with Virtual Nodes:

```
Physical servers: A, B
Virtual nodes per server: 3

Ring:
        0°
        │
   A#2  │  A#0 (45°)
  (320°)│ /
       \│/
        │
   B#1 ─┼─ B#0 (90°)
  (200°)│
       /│\
      / │ \
   B#2  │  A#1 (150°)
  (250°)

Now load is distributed more evenly!
```

Benefits of Virtual Nodes

ASPECT	WITHOUT VNODES	WITH VNODES
Load Distribution	Uneven	Even
Adding Node	Affects 1 range	Affects many small ranges
Heterogeneous Hardware	Not supported	Supported (more vnodes for powerful servers)
Failure Impact	Large chunk unavailable	Small chunks distributed

Handling Heterogeneous Hardware

```
# More powerful servers get more virtual nodes
server_vnodes = {
    "server-A": 100,   # Standard server
    "server-B": 100,   # Standard server
    "server-C": 200,   # 2x capacity server
    "server-D": 50,    # Half capacity server
}

# server-C handles ~2x the load of A or B
# server-D handles ~0.5x the load of A or B
```

Choosing the Number of Virtual Nodes

```
Factors to consider:
- More vnodes = better distribution, but more memory for ring
- Typical range: 100-200 vnodes per physical node
- Amazon DynamoDB uses 256 vnodes per node

Memory calculation:
- 100 physical nodes × 150 vnodes = 15,000 ring entries
- Each entry: ~100 bytes (position + server reference)
- Total: ~1.5 MB (negligible)
```

4. Rebalancing & Data Migration (10 min)

When Rebalancing Occurs

1. **Node Addition:** New server joins the cluster
2. **Node Removal:** Server leaves (planned or failure)
3. **Capacity Change:** Adjusting virtual node count

Rebalancing Strategy

Adding a Node:

```
def add_node(ring, new_server, num_vnodes=150):
    """Add a new server to the ring"""
    keys_to_migrate = {}

    for i in range(num_vnodes):
        vnode_key = f"{new_server}#vnode{i}"
        new_position = hash_to_ring(vnode_key)

        # Find the server that currently owns this position
        current_owner = find_server_at_position(ring, new_position)

        # Keys between previous position and new position move to new server
        prev_position = find_previous_position(ring, new_position)
        keys_to_migrate[new_position] = {
            'from': current_owner,
            'range': (prev_position, new_position)
        }

        # Add new vnode to ring
        ring[new_position] = new_server

    return keys_to_migrate
```

Migration Process:

```
Step 1: Add new node to ring (metadata only)
Step 2: New node starts accepting writes for its range
Step 3: Background migration of existing keys
Step 4: Old node stops serving migrated keys

Timeline:
t=0    [Add to ring]
t=1    [Accept new writes]
t=2-10 [Background migration]
t=11   [Complete]
```

Handling Node Failures

Graceful Removal:

```python
        def remove_node_graceful(ring, server):
            """Gracefully remove a server"""
            # 1. Stop accepting new writes
            server.stop_writes()

            # 2. Migrate data to successor nodes
            for vnode_position in get_vnodes(ring, server):
                successor = find_next_server(ring, vnode_position)
                migrate_data(server, successor, vnode_position)

            # 3. Remove from ring
            remove_vnodes(ring, server)
```

Sudden Failure:

```
When a node fails unexpectedly:
1. Detect failure (heartbeat timeout)
2. Remove from ring immediately
3. Successor nodes now responsible for failed node's range
4. If replication exists, replicas serve requests
5. Re-replicate data to maintain replication factor
```

Data Replication with Consistent Hashing

```
Replication Factor: 3
Strategy: Replicate to N-1 successor nodes

Key "user:123" at position 80°:
- Primary: server-B (120°)
- Replica 1: server-E (150°)
- Replica 2: server-C (200°)

        0°
        |
        |    A (45°)
       /|\
      / | \
  D   |   B (120°) ← Primary
(300°)|    \
     \|     E (150°) ← Replica 1
      |    /
  C (200°) ← Replica 2
```

5. Implementation & Real-World Applications (15 min)

Complete Implementation

```python
import hashlib
from bisect import bisect_right

class ConsistentHashRing:
    def __init__(self, num_vnodes=150):
        self.num_vnodes = num_vnodes
        self.ring = {}  # position → server
        self.sorted_positions = []
        self.servers = set()

    def _hash(self, key):
        """Generate hash for a key"""
        return int(hashlib.md5(key.encode()).hexdigest(), 16)

    def add_server(self, server):
        """Add a server with virtual nodes"""
        self.servers.add(server)
        for i in range(self.num_vnodes):
            vnode_key = f"{server}#vnode{i}"
            position = self._hash(vnode_key)
            self.ring[position] = server

        self.sorted_positions = sorted(self.ring.keys())

    def remove_server(self, server):
        """Remove a server and its virtual nodes"""
        self.servers.discard(server)
        positions_to_remove = [
            pos for pos, srv in self.ring.items() if srv == server
        ]
        for pos in positions_to_remove:
            del self.ring[pos]

        self.sorted_positions = sorted(self.ring.keys())

    def get_server(self, key):
        """Find the server responsible for a key"""
        if not self.ring:
            return None

        key_hash = self._hash(key)
        # Find first position ≥ key_hash
        idx = bisect_right(self.sorted_positions, key_hash)

        # Wrap around if necessary
        if idx == len(self.sorted_positions):
            idx = 0

        position = self.sorted_positions[idx]
        return self.ring[position]

    def get_servers_for_replication(self, key, replicas=3):
        """Get N servers for replication"""
        if not self.ring or replicas > len(self.servers):
            return list(self.servers)

        key_hash = self._hash(key)
        idx = bisect_right(self.sorted_positions, key_hash)

        servers = []
        seen = set()

        while len(servers) < replicas:
            if idx ≥ len(self.sorted_positions):
                idx = 0

            server = self.ring[self.sorted_positions[idx]]
            if server not in seen:
                servers.append(server)
                seen.add(server)

            idx += 1

        return servers

# Usage
ring = ConsistentHashRing(num_vnodes=150)
ring.add_server("server-A")
ring.add_server("server-B")
ring.add_server("server-C")

# Find server for a key
server = ring.get_server("user:12345")
print(f"user:12345 → {server}")
```

```
        # Get replicas
        replicas = ring.get_servers_for_replication("user:12345", replicas=3)
        print(f"Replicas: {replicas}")
```

Real-World Applications

1. Amazon DynamoDB

```
DynamoDB Partitioning:
- Uses consistent hashing for partition key distribution
- 256 virtual nodes per physical partition
- Automatic rebalancing during scaling

Partition Key → Hash → Partition
"user:123"    → 0x7F... → Partition-B
```

2. Apache Cassandra

```
Cassandra Token Ring:
- Each node owns a range of tokens
- Virtual nodes (vnodes) enabled by default
- Configurable replication factor

CREATE KEYSPACE my_keyspace
WITH replication = {
    'class': 'NetworkTopologyStrategy',
    'datacenter1': 3
};
```

3. Redis Cluster

```
Redis Cluster:
- 16384 hash slots (not continuous ring)
- Each node owns a subset of slots
- Manual or automatic slot migration

CLUSTER ADDSLOTS 0 1 2 3 ... 5460  # Node A
CLUSTER ADDSLOTS 5461 ... 10922   # Node B
CLUSTER ADDSLOTS 10923 ... 16383  # Node C
```

4. Content Delivery Networks (CDNs)

```
CDN Edge Server Selection:
- Hash(content_url) → Edge server
- Ensures same content always served from same edge
- Maximizes cache hit rate

Request: GET /images/logo.png
Hash: 0x3F...
Edge: edge-server-tokyo-2
```

Load Balancing with Consistent Hashing

```python
        class ConsistentHashLoadBalancer:
            def __init__(self):
                self.ring = ConsistentHashRing(num_vnodes=100)
                self.server_health = {}

            def add_backend(self, server, weight=1):
                """Add backend server with optional weight"""
                # More vnodes for higher weight
                vnodes = 100 * weight
                self.ring.num_vnodes = vnodes
                self.ring.add_server(server)
                self.server_health[server] = True

            def get_backend(self, request_key):
                """Get backend for a request"""
                # Use session ID or client IP as key for sticky sessions
                server = self.ring.get_server(request_key)

                # Health check
                if not self.server_health.get(server, False):
                    # Fallback to next healthy server
                    return self._get_next_healthy(request_key)

                return server

            def _get_next_healthy(self, key):
                """Find next healthy server on the ring"""
                servers = self.ring.get_servers_for_replication(key,

replicas=len(self.ring.servers))
                for server in servers:
                    if self.server_health.get(server, False):
                        return server
                return None
```

🚨 Common Pitfalls & Solutions

1. Hot Spots

Problem: Some keys are accessed much more frequently.

```
Popular user "celebrity:123" → server-B
Server-B gets 100x more traffic than others
```

Solutions: - Add read replicas for hot keys - Cache hot keys at application layer - Split hot keys across multiple entries

2. Uneven Virtual Node Distribution

Problem: Random hashing can still create clusters.

Solution: Use deterministic placement or jump consistent hashing.

```
        # Jump Consistent Hash (Google)
        def jump_consistent_hash(key, num_buckets):
            b, j = -1, 0
            while j < num_buckets:
                b = j
                key = ((key * 2862933555777941757) + 1) & 0xFFFFFFFFFFFFFFFF
                j = int((b + 1) * (float(1 << 31) / float((key >> 33) + 1)))
            return b
```

3. Ring Metadata Synchronization

Problem: All nodes need consistent view of the ring.

Solutions: - Gossip protocol (Cassandra) - Centralized coordinator (ZooKeeper) - Consensus algorithm (Raft)

4. Data Migration During Rebalancing

Problem: Large data movement affects performance.

Solutions: - Background migration with rate limiting - Dual-write during transition - Lazy migration (migrate on access)

📊 Comparison with Alternatives

APPROACH	REDISTRIBUTION	COMPLEXITY	USE CASE
Modulo Hash	~100% on change	Low	Static clusters
Consistent Hash	~K/N on change	Medium	Dynamic clusters
Rendezvous Hash	~K/N on change	Medium	When order matters
Jump Hash	~K/N on change	Low	Memory-constrained

✅ Key Takeaways

1. **Consistent hashing minimizes data movement** when scaling clusters
2. **Virtual nodes ensure even distribution** and support heterogeneous hardware
3. **The hash ring is a fundamental building block** for distributed databases and caches
4. **Replication integrates naturally** by using successor nodes
5. **Real systems like DynamoDB, Cassandra, and Redis** all use variants of consistent hashing

💡 Practical Exercise

Scenario: Design a distributed cache for a social media platform.

Requirements: - 10 cache servers initially - Must scale to 50 servers - Session data must be sticky (same user → same server) - Handle server failures gracefully

Questions: 1. How many virtual nodes per server? 2. How to handle user session stickiness? 3. What happens when a server fails? 4. How to migrate data when adding servers?

📝 Quick Reference

Hash Ring Operations

```
# Add server
ring.add_server("server-new")

# Remove server
ring.remove_server("server-old")

# Find server for key
server = ring.get_server("my-key")

# Get replicas
replicas = ring.get_servers_for_replication("my-key", n=3)
```

Key Formulas

```
Keys remapped (modulo): (N-1)/N ≈ 100% for large N
Keys remapped (consistent): K/N where K=total keys, N=nodes

Virtual nodes memory: nodes × vnodes × ~100 bytes
Recommended vnodes: 100-256 per physical node
```

Session End - Thank You! 🎉

#consistent-hashing #distributed-systems #partitioning #architecture #session-notes