# Distributed Cache System

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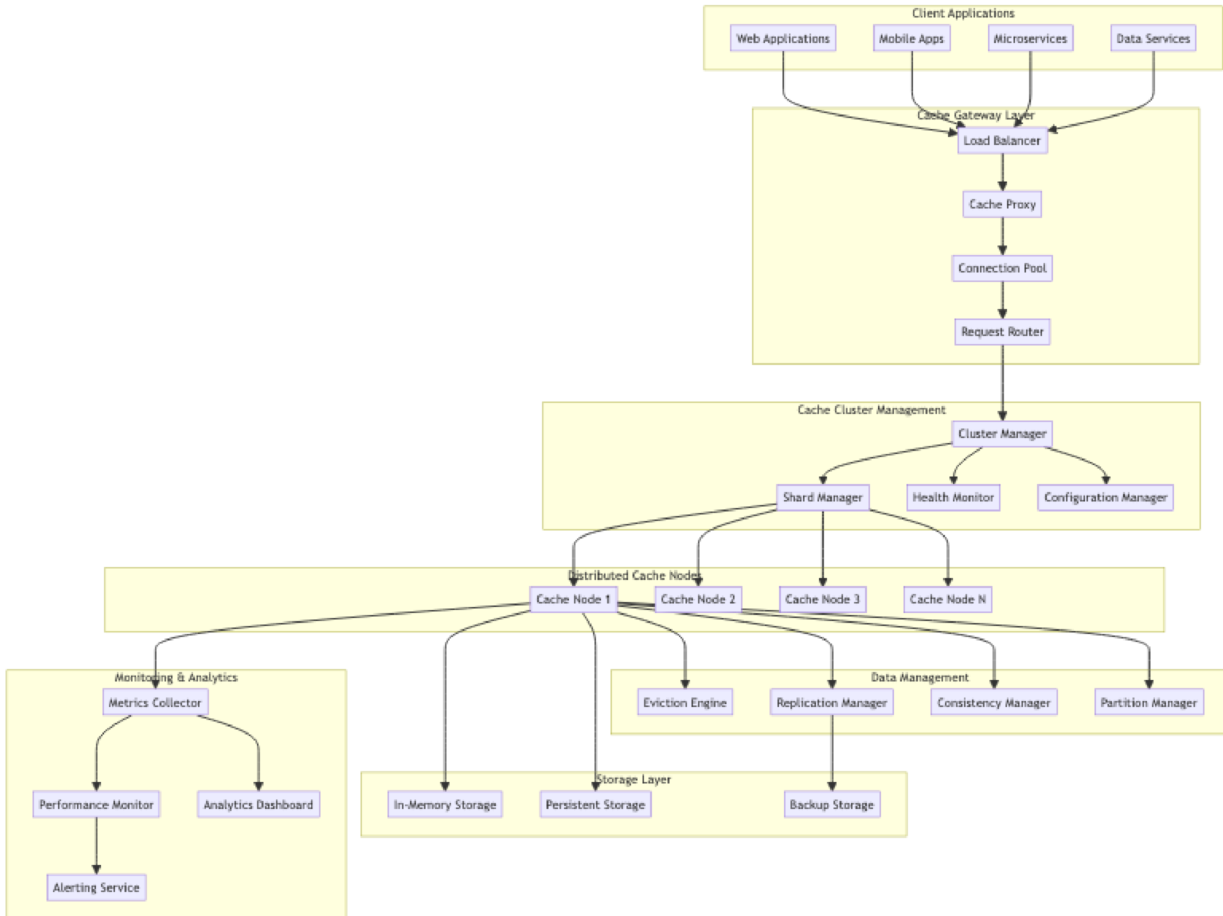


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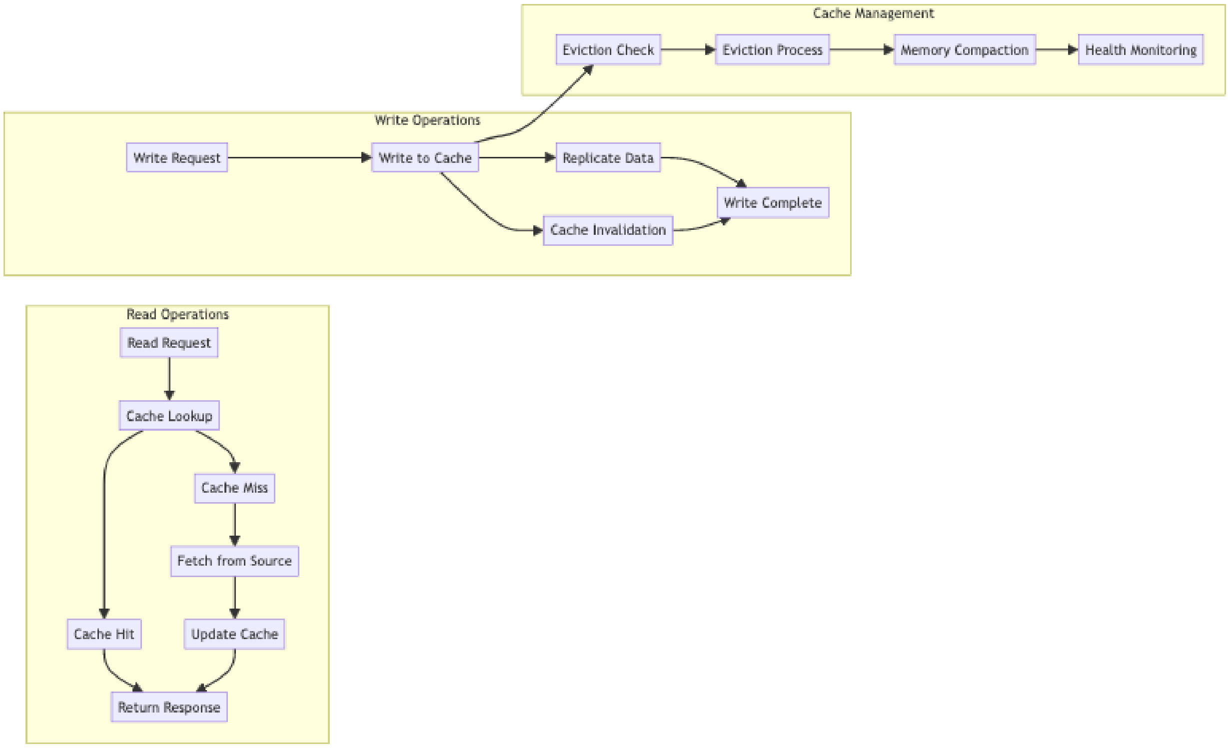


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### Consistent Hashing for Sharding

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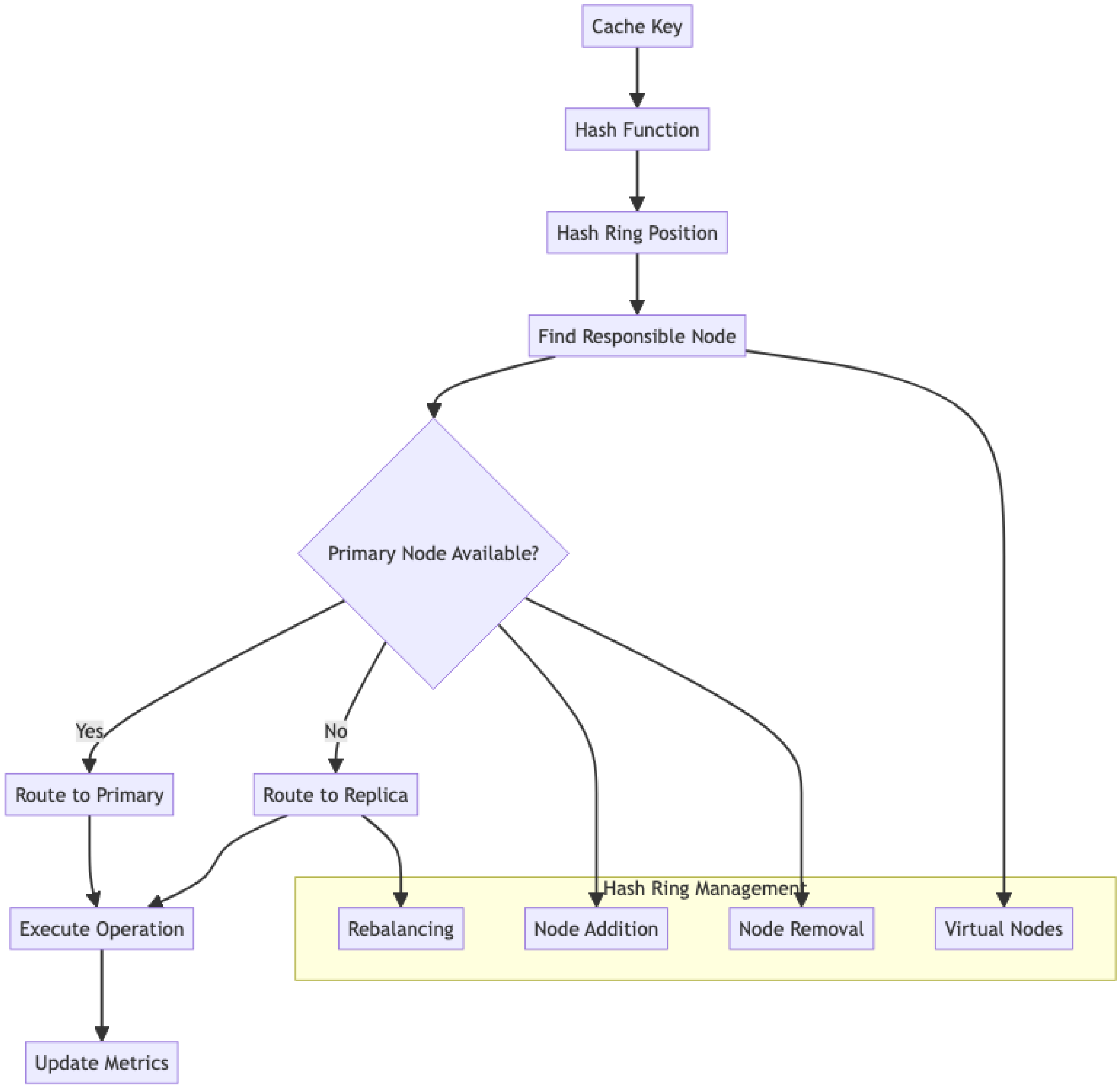


### Multi-Level Cache Architecture

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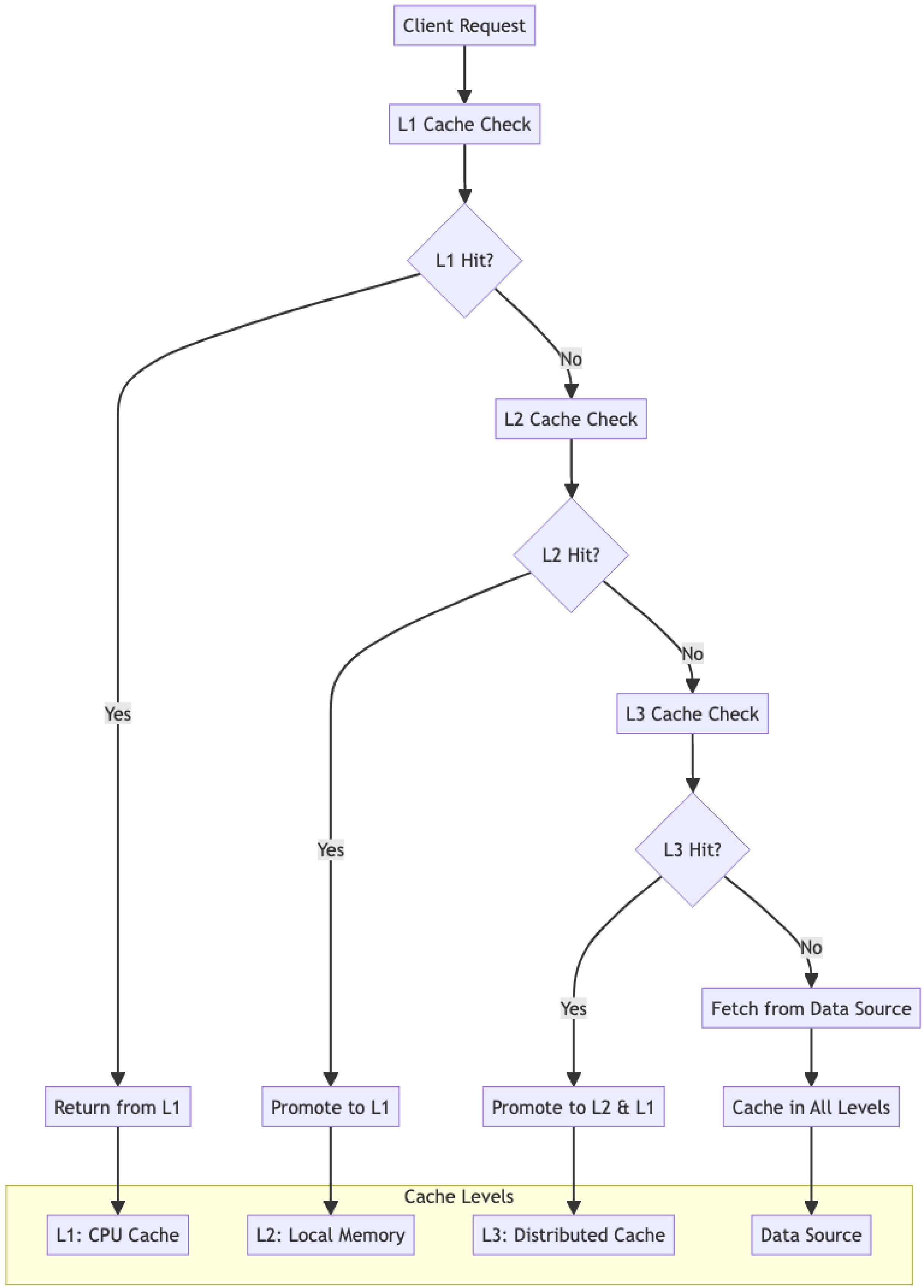
Client Request
L1 Cache Check
L1 Hit?
Yes
No
L2 Cache Check
L2 Hit?
Yes
No
L3 Cache Check
L3 Hit?
Yes
No
Fetch from Data Source
Return from L1
Promote to L1
Promote to L2 & L1
Cache in All Levels
Cache Levels
L1: CPU Cache
L2: Local Memory
L3: Distributed Cache
Data Source

### Cache Consistency Model

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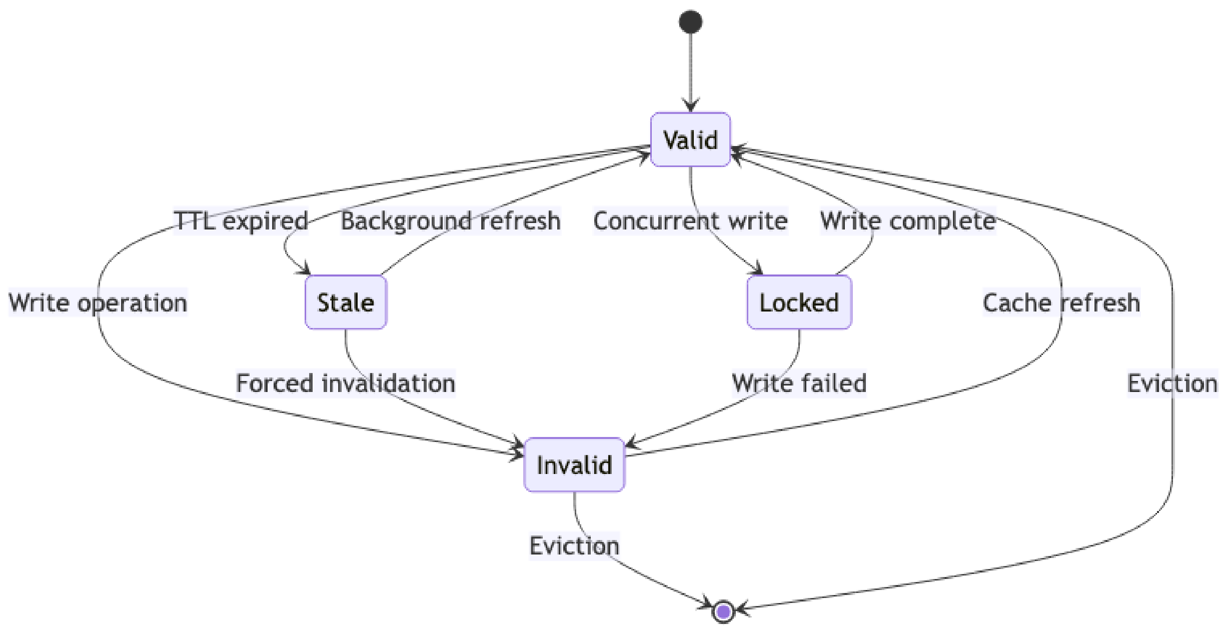


## Core Algorithms

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### 1. Consistent Hashing with Virtual Nodes

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**Purpose**: Distribute cache keys evenly across nodes and minimize data movement during cluster changes.

**Consistent Hashing Implementation**:

```
ConsistentHashConfig = {
  virtualNodesPerPhysicalNode: 160,    // Virtual nodes for better distribution
  hashFunction: 'sha1',                // Hash function for ring positions
  replicationFactor: 3,                // Number of replicas per key
  maxLoadFactor: 1.25,                 // Maximum load imbalance allowed

  rebalanceThreshold: 0.1,             // Trigger rebalance at 10% imbalance
```

```
  migrationBatchSize: 1000,           // Keys per migration batch
  migrationTimeout: 30000             // 30 seconds per batch
}

class ConsistentHashRing:
  constructor(config):
    this.config = config
    this.ring = new Map()             // position -> node mapping
    this.nodes = new Map()            // nodeId -> node info
    this.virtualNodes = new Map()     // virtualNodeId -> nodeId
    this.sortedPositions = []         // Sorted ring positions

  function addNode(nodeId, nodeInfo):
    this.nodes.set(nodeId, nodeInfo)

    // Create virtual nodes for this physical node
    for i in range(this.config.virtualNodesPerPhysicalNode):
      virtualNodeId = `${nodeId}:${i}`
      position = this.hashToPosition(`${virtualNodeId}`)

      this.ring.set(position, nodeId)
      this.virtualNodes.set(virtualNodeId, nodeId)
      this.sortedPositions.push(position)

    // Re-sort positions after adding new virtual nodes
    this.sortedPositions.sort((a, b) => a - b)

    // Trigger rebalancing if needed
    if this.shouldRebalance():
      this.rebalanceCluster()

  function removeNode(nodeId):
    // Remove all virtual nodes for this physical node
    virtualNodesToRemove = []

    for [virtualNodeId, physicalNodeId] of this.virtualNodes:
      if physicalNodeId === nodeId:
        virtualNodesToRemove.push(virtualNodeId)

    for virtualNodeId in virtualNodesToRemove:
      position = this.hashToPosition(virtualNodeId)
      this.ring.delete(position)
      this.virtualNodes.delete(virtualNodeId)
      this.sortedPositions = this.sortedPositions.filter(p => p !== position)
```

```
  this.nodes.delete(nodeId)

  // Trigger rebalancing
  this.rebalanceCluster()

function getResponsibleNodes(key):
  if this.sortedPositions.length === 0:
    return []

  keyPosition = this.hashToPosition(key)
  responsibleNodes = []

  // Find the first node position >= key position
  startIndex = this.binarySearch(keyPosition)

  // Collect replicas
  uniqueNodes = new Set()
  index = startIndex

  while uniqueNodes.size < this.config.replicationFactor and uniqueNodes.size < this.n
    position = this.sortedPositions[index % this.sortedPositions.length]
    nodeId = this.ring.get(position)

    if not uniqueNodes.has(nodeId):
      uniqueNodes.add(nodeId)
      responsibleNodes.push({
        nodeId: nodeId,
        position: position,
        isPrimary: uniqueNodes.size === 1
      })

    index = (index + 1) % this.sortedPositions.length

  return responsibleNodes

function hashToPosition(input):
  hash = crypto.createHash(this.config.hashFunction).update(input).digest('hex')
  // Convert first 8 characters of hex to integer
  return parseInt(hash.substring(0, 8), 16)

function shouldRebalance():
  if this.nodes.size < 2:
    return false

  // Calculate load distribution
```

```
    loadDistribution = this.calculateLoadDistribution()
    maxLoad = Math.max(...loadDistribution.values())
    minLoad = Math.min(...loadDistribution.values())
    avgLoad = Array.from(loadDistribution.values()).reduce((a, b) => a + b) / loadDistri

    loadFactor = maxLoad / avgLoad
    imbalance = (maxLoad - minLoad) / avgLoad

    return loadFactor > this.config.maxLoadFactor or imbalance > this.config.rebalanceTh
```

**Data Migration Algorithm**:

```
function rebalanceCluster():
  // Calculate current and target key distributions
  currentDistribution = this.calculateCurrentDistribution()
  targetDistribution = this.calculateTargetDistribution()

  // Generate migration plan
  migrationPlan = this.generateMigrationPlan(currentDistribution, targetDistribution)

  if migrationPlan.totalKeys === 0:
    return // No migration needed

  // Execute migration in batches
  for batch in migrationPlan.batches:
    this.executeMigrationBatch(batch)

function executeMigrationBatch(batch):
  migrationTasks = []

  for migration in batch.migrations:
    task = {
      keys: migration.keys,
      sourceNode: migration.sourceNode,
      targetNode: migration.targetNode,
      batchId: batch.id
    }

    migrationTasks.push(this.migrateKeyBatch(task))

  // Execute all migrations in parallel
  results = await Promise.allSettled(migrationTasks)

  // Handle migration failures
  failedMigrations = results.filter(r => r.status === 'rejected')
```

```
  if failedMigrations.length > 0:
    this.handleMigrationFailures(failedMigrations, batch)

function migrateKeyBatch(task):
  sourceNode = this.nodes.get(task.sourceNode)
  targetNode = this.nodes.get(task.targetNode)

  migratedKeys = []

  for key in task.keys:
    try:
      // Get data from source node
      data = sourceNode.get(key)

      if data:
        // Write to target node
        writeSuccess = targetNode.set(key, data.value, data.ttl)

        if writeSuccess:
          // Verify write
          verifyData = targetNode.get(key)

          if verifyData and verifyData.value === data.value:
            // Remove from source node
            sourceNode.delete(key)
            migratedKeys.push(key)
          else:
            throw new Error(`Verification failed for key: ${key}`)
        else:
          throw new Error(`Write failed for key: ${key}`)

    catch error:
      logMigrationError(task.batchId, key, error)
      throw error

  return {
    batchId: task.batchId,
    migratedKeys: migratedKeys,
    sourceNode: task.sourceNode,
    targetNode: task.targetNode
  }
```

### 2. Advanced Eviction Algorithms

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**Purpose**: Optimize cache performance by intelligently removing least valuable data when memory is full.

**Multi-Factor LRU with Frequency and Cost**:

```
EvictionConfig = {
  algorithm: 'adaptive_lru',          // 'lru', 'lfu', 'lru_k', 'adaptive_lru'
  memoryThreshold: 0.85,              // Trigger eviction at 85% memory
  evictionBatchSize: 100,             // Evict in batches
  costAwareEviction: true,            // Consider fetch cost in eviction

  frequencyWindow: 3600000,           // 1 hour frequency window
  agingFactor: 0.9,                   // Decay factor for aging frequency
  costWeight: 0.3,                    // Weight for fetch cost in scoring
  sizeWeight: 0.2,                    // Weight for entry size in scoring
  frequencyWeight: 0.5                // Weight for access frequency
}

class AdaptiveLRUCache:
  constructor(config):
    this.config = config
    this.cache = new Map()            // key -> cache entry
    this.accessOrder = new DoublyLinkedList()  // LRU ordering
    this.frequencyCounter = new Map()   // key -> frequency info
    this.sizeTracker = new SizeTracker()
    this.evictionCandidates = new MinHeap()

  function get(key):
    entry = this.cache.get(key)

    if not entry:
      return null

    // Update access information
    this.updateAccessInfo(key, entry)

    // Move to front of LRU list
    this.accessOrder.moveToFront(entry.listNode)

    return entry.value

  function set(key, value, ttl = null, fetchCost = 1):
    // Check if eviction is needed
    if this.shouldEvict():
```

```
    this.performEviction()

  entry = {
    key: key,
    value: value,
    ttl: ttl,
    expiresAt: ttl ? Date.now() + ttl : null,
    createdAt: Date.now(),
    lastAccessed: Date.now(),
    accessCount: 1,
    fetchCost: fetchCost,
    size: this.calculateSize(value),
    listNode: null
  }

  // Add to LRU list
  entry.listNode = this.accessOrder.addToFront(entry)

  // Store in cache
  this.cache.set(key, entry)

  // Initialize frequency tracking
  this.frequencyCounter.set(key, {
    count: 1,
    firstAccess: Date.now(),
    lastUpdate: Date.now()
  })

  // Update size tracking
  this.sizeTracker.add(entry.size)

function shouldEvict():
  memoryUsage = this.sizeTracker.totalSize / this.sizeTracker.maxSize
  return memoryUsage > this.config.memoryThreshold

function performEviction():
  // Calculate eviction scores for all entries
  evictionCandidates = []

  for [key, entry] of this.cache:
    if this.isExpired(entry):
      // Expired entries have highest priority for eviction
      evictionCandidates.push({ key, score: Infinity })
    else:
      score = this.calculateEvictionScore(key, entry)
```

```
      evictionCandidates.push({ key, score })

  // Sort by eviction score (higher score = more likely to evict)
  evictionCandidates.sort((a, b) => b.score - a.score)

  // Evict entries in batches
  evictedCount = 0
  targetEvictionCount = Math.min(
    this.config.evictionBatchSize,
    Math.ceil(this.cache.size * 0.1) // Evict at most 10% of cache
  )

  for candidate in evictionCandidates:
    if evictedCount >= targetEvictionCount:
      break

    this.evictEntry(candidate.key)
    evictedCount++

    // Stop if we've freed enough memory
    if not this.shouldEvict():
      break

function calculateEvictionScore(key, entry):
  score = 0

  // Recency factor (higher = more recently used = lower eviction score)
  timeSinceAccess = Date.now() - entry.lastAccessed
  recencyScore = timeSinceAccess / (24 * 60 * 60 * 1000) // Normalize to days

  // Frequency factor
  frequencyInfo = this.frequencyCounter.get(key)
  frequencyScore = this.calculateFrequencyScore(frequencyInfo)

  // Size factor (larger entries get higher eviction score)
  sizeScore = entry.size / this.sizeTracker.averageSize

  // Cost factor (expensive-to-fetch entries get lower eviction score)
  costScore = 1 / (entry.fetchCost + 1)

  // Combine factors
  score = (recencyScore * (1 - this.config.frequencyWeight)) +
          (frequencyScore * this.config.frequencyWeight) +
          (sizeScore * this.config.sizeWeight) +
          (costScore * this.config.costWeight)
```

```
    return score

  function calculateFrequencyScore(frequencyInfo):
    if not frequencyInfo:
      return 1.0 // High eviction score for entries without frequency data

    // Apply aging to frequency count
    timeElapsed = Date.now() - frequencyInfo.lastUpdate
    agingFactor = Math.pow(this.config.agingFactor, timeElapsed / this.config.frequencyW

    adjustedFrequency = frequencyInfo.count * agingFactor

    // Normalize frequency (lower frequency = higher eviction score)
    return 1 / (adjustedFrequency + 1)
```

### 3. Cache Warming and Prefetching Strategy

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**Purpose**: Proactively load frequently accessed data and predict future access patterns to improve cache hit rates.

**Intelligent Cache Warming**:

```
WarmingConfig = {
  warmingStrategies: ['historical', 'predictive', 'pattern_based'],
  warmingThreshold: 0.7,              // Start warming at 70% cache capacity
  maxWarmingConcurrency: 10,          // Max concurrent warming operations

  historicalWindow: 86400000,         // 24 hours historical data
  predictionAccuracyThreshold: 0.6,   // Minimum 60% prediction accuracy
  patternDetectionWindow: 3600000,    // 1 hour for pattern detection

  prefetchDistance: 5,                // Number of related keys to prefetch
  prefetchProbabilityThreshold: 0.4   // Minimum 40% probability to prefetch
}

class CacheWarmingEngine:
  constructor(config):
    this.config = config
    this.accessHistory = new TimeSeriesDB()
    this.patternDetector = new PatternDetector()
    this.predictiveModel = new AccessPredictor()
    this.warmingQueue = new PriorityQueue()
```

```
function initiateCacheWarming():
  // Analyze current cache state
  cacheStats = this.analyzeCacheState()

  if cacheStats.hitRate < this.config.warmingThreshold:
    // Trigger warming strategies
    this.executeWarmingStrategies(cacheStats)

function executeWarmingStrategies(cacheStats):
  warmingTasks = []

  // Historical warming - warm frequently accessed keys
  if this.config.warmingStrategies.includes('historical'):
    historicalKeys = this.getHistoricallyPopularKeys()
    warmingTasks.push(...this.createWarmingTasks(historicalKeys, 'historical'))

  // Predictive warming - warm predicted future accesses
  if this.config.warmingStrategies.includes('predictive'):
    predictedKeys = this.predictFutureAccesses()
    warmingTasks.push(...this.createWarmingTasks(predictedKeys, 'predictive'))

  // Pattern-based warming - warm based on detected patterns
  if this.config.warmingStrategies.includes('pattern_based'):
    patternKeys = this.detectAccessPatterns()
    warmingTasks.push(...this.createWarmingTasks(patternKeys, 'pattern_based'))

  // Execute warming tasks with concurrency control
  this.executeWarmingTasks(warmingTasks)

function getHistoricallyPopularKeys():
  // Query access history for frequently accessed keys
  endTime = Date.now()
  startTime = endTime - this.config.historicalWindow

  accessCounts = this.accessHistory.getAccessCounts(startTime, endTime)

  // Sort by access frequency and return top keys
  sortedKeys = Object.entries(accessCounts)
    .sort(([,a], [,b]) => b - a)
    .slice(0, 1000) // Top 1000 keys
    .map(([key, count]) => ({ key, priority: count, strategy: 'historical' }))

  return sortedKeys
```

```
function predictFutureAccesses():
  // Use machine learning model to predict future accesses
  currentTime = Date.now()
  contextFeatures = this.extractContextFeatures(currentTime)

  predictions = this.predictiveModel.predict(contextFeatures)

  // Filter predictions by confidence threshold
  confidentPredictions = predictions.filter(p =>
    p.confidence >= this.config.predictionAccuracyThreshold
  )

  return confidentPredictions.map(p => ({
    key: p.key,
    priority: p.confidence,
    strategy: 'predictive'
  }))

function detectAccessPatterns():
  // Detect sequential, batch, and temporal access patterns
  patterns = this.patternDetector.detectPatterns(this.config.patternDetectionWindow)

  patternKeys = []

  for pattern in patterns:
    switch pattern.type:
      case 'sequential':
        patternKeys.push(...this.generateSequentialKeys(pattern))
        break
      case 'batch':
        patternKeys.push(...this.generateBatchKeys(pattern))
        break
      case 'temporal':
        patternKeys.push(...this.generateTemporalKeys(pattern))
        break

  return patternKeys

function createWarmingTasks(keys, strategy):
  tasks = []

  for keyInfo in keys:
    task = {
      key: keyInfo.key,
      priority: keyInfo.priority,
```

```
        strategy: strategy,
        createdAt: Date.now(),
        retries: 0
      }

      tasks.push(task)

    return tasks

  function executeWarmingTasks(tasks):
    // Sort tasks by priority
    sortedTasks = tasks.sort((a, b) => b.priority - a.priority)

    // Execute with concurrency control
    concurrentTasks = 0
    taskQueue = [...sortedTasks]

    while taskQueue.length > 0 and concurrentTasks < this.config.maxWarmingConcurrency:
      task = taskQueue.shift()
      concurrentTasks++

      this.executeWarmingTask(task).finally(() => {
        concurrentTasks--

        // Continue processing remaining tasks
        if taskQueue.length > 0:
          nextTask = taskQueue.shift()
          this.executeWarmingTask(nextTask)
      })
```

**Predictive Prefetching Algorithm**:

```
function executeWarmingTask(task):
  try:
    // Check if key is already in cache
    if this.cache.has(task.key):
      return { success: true, reason: 'already_cached' }

    // Fetch data from source
    data = await this.fetchFromDataSource(task.key)

    if data:
      // Calculate appropriate TTL based on access patterns
      ttl = this.calculateOptimalTTL(task.key, task.strategy)

      // Add to cache with lower priority (won't evict existing entries)
```

```
      this.cache.setWithPriority(task.key, data, ttl, 'warming')

      // Trigger related key prefetching
      if this.shouldPrefetchRelated(task):
        this.prefetchRelatedKeys(task.key, data)

      return { success: true, warmed: true }
    else:
      return { success: false, reason: 'data_not_found' }

  catch error:
    logWarmingError(task, error)

    // Retry with exponential backoff
    if task.retries < 3:
      task.retries++
      retryDelay = Math.pow(2, task.retries) * 1000

      setTimeout(() => {
        this.executeWarmingTask(task)
      }, retryDelay)

    return { success: false, reason: 'fetch_error', error: error }

function prefetchRelatedKeys(key, data):
  // Identify related keys based on various strategies
  relatedKeys = []

  // Content-based similarity
  contentKeys = this.findContentSimilarKeys(key, data)
  relatedKeys.push(...contentKeys)

  // Access pattern correlation
  correlatedKeys = this.findCorrelatedKeys(key)
  relatedKeys.push(...correlatedKeys)

  // Hierarchical relationships (parent/child keys)
  hierarchicalKeys = this.findHierarchicalKeys(key)
  relatedKeys.push(...hierarchicalKeys)

  // Limit prefetch count and filter by probability
  candidateKeys = relatedKeys
    .filter(k => k.probability >= this.config.prefetchProbabilityThreshold)
    .sort((a, b) => b.probability - a.probability)
    .slice(0, this.config.prefetchDistance)
```

```
  // Schedule prefetch tasks
  for candidate in candidateKeys:
    prefetchTask = {
      key: candidate.key,
      priority: candidate.probability,
      strategy: 'prefetch',
      parentKey: key,
      createdAt: Date.now()
    }

    this.warmingQueue.enqueue(prefetchTask)
```

### 4. Multi-Tier Cache Coherence Algorithm

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**Purpose**: Maintain consistency across multiple cache tiers while optimizing for performance and reducing coordination overhead.

**Write-Through with Lazy Propagation**:

```
CoherenceConfig = {
  coherenceProtocol: 'write_through_lazy',  // 'write_through', 'write_back', 'write_thr
  invalidationStrategy: 'time_based',       // 'immediate', 'time_based', 'version_based
  maxStaleTime: 60000,                      // 1 minute max staleness

  propagationBatchSize: 100,                // Batch invalidations
  propagationInterval: 5000,                // 5 seconds batch interval
  consistencyLevel: 'eventual',             // 'strong', 'eventual', 'weak'

  conflictResolution: 'timestamp',          // 'timestamp', 'version', 'manual'
}

class CacheCoherenceManager:
  constructor(config):
    this.config = config
    this.invalidationQueue = new BatchQueue()
    this.versionTracker = new Map()
    this.coherenceLog = new CircularBuffer(10000)

  function handleWrite(key, value, sourceNode):
    writeTimestamp = Date.now()
    version = this.incrementVersion(key)
```

```
  writeOperation = {
    key: key,
    value: value,
    version: version,
    timestamp: writeTimestamp,
    sourceNode: sourceNode,
    operation: 'write'
  }

  switch this.config.coherenceProtocol:
    case 'write_through':
      return this.executeWriteThrough(writeOperation)
    case 'write_back':
      return this.executeWriteBack(writeOperation)
    case 'write_through_lazy':
      return this.executeWriteThroughLazy(writeOperation)

function executeWriteThroughLazy(writeOperation):
  // Write to local cache immediately
  localSuccess = this.writeToLocalCache(writeOperation)

  if not localSuccess:
    return { success: false, reason: 'local_write_failed' }

  // Queue for lazy propagation to other nodes
  this.queuePropagation(writeOperation)

  // Write to persistent storage if configured
  if this.hasPersistentStorage():
    this.writeToStorage(writeOperation)

  return { success: true, version: writeOperation.version }

function queuePropagation(writeOperation):
  propagationTask = {
    operation: writeOperation,
    queuedAt: Date.now(),
    attempts: 0,
    maxAttempts: 3
  }

  this.invalidationQueue.add(propagationTask)

  // Process batch if queue is full or interval elapsed
  if this.invalidationQueue.shouldProcess():
```

```
    this.processPropagationBatch()

function processPropagationBatch():
  batch = this.invalidationQueue.getBatch(this.config.propagationBatchSize)

  if batch.length === 0:
    return

  // Group operations by target nodes
  nodeOperations = this.groupOperationsByNode(batch)

  // Send invalidations to each node
  propagationPromises = []

  for [nodeId, operations] of nodeOperations:
    promise = this.sendInvalidationBatch(nodeId, operations)
    propagationPromises.push(promise)

  // Handle propagation results
  Promise.allSettled(propagationPromises).then(results => {
    this.handlePropagationResults(results, batch)
  })

function sendInvalidationBatch(nodeId, operations):
  return new Promise((resolve, reject) => {
    invalidationMessage = {
      type: 'cache_invalidation_batch',
      operations: operations.map(op => ({
        key: op.operation.key,
        version: op.operation.version,
        timestamp: op.operation.timestamp,
        action: this.determineInvalidationAction(op.operation)
      })),
      sourceNode: this.nodeId,
      batchId: generateBatchId()
    }

    this.sendToNode(nodeId, invalidationMessage)
      .then(response => {
        if response.success:
          resolve({ nodeId, operations, success: true })
        else:
          reject({ nodeId, operations, error: response.error })
      })
      .catch(error => {
```

```
      reject({ nodeId, operations, error })
    })
  })

function handleInvalidationMessage(message):
  processedOperations = []

  for operation in message.operations:
    result = this.processInvalidationOperation(operation)
    processedOperations.push({
      key: operation.key,
      success: result.success,
      reason: result.reason
    })

  // Send acknowledgment back
  acknowledgment = {
    type: 'invalidation_ack',
    batchId: message.batchId,
    sourceNode: message.sourceNode,
    results: processedOperations
  }

  this.sendToNode(message.sourceNode, acknowledgment)

function processInvalidationOperation(operation):
  currentVersion = this.versionTracker.get(operation.key)

  // Check if invalidation is still relevant
  if currentVersion and currentVersion >= operation.version:
    return { success: true, reason: 'version_already_newer' }

  switch operation.action:
    case 'invalidate':
      return this.invalidateKey(operation.key, operation.version)
    case 'update':
      return this.updateKey(operation.key, operation.value, operation.version)
    case 'delete':
      return this.deleteKey(operation.key, operation.version)

  return { success: false, reason: 'unknown_action' }

function invalidateKey(key, version):
  try:
    // Remove from cache
```

```
    this.cache.delete(key)

    // Update version tracker
    this.versionTracker.set(key, version)

    // Log invalidation
    this.coherenceLog.add({
      action: 'invalidate',
      key: key,
      version: version,
      timestamp: Date.now()
    })

    return { success: true }

  catch error:
    return { success: false, reason: 'invalidation_error', error: error }
```

### 5. Performance Monitoring and Auto-Scaling

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**Purpose**: Monitor cache performance metrics and automatically scale cache resources based on load and performance patterns.

**Adaptive Scaling Algorithm**:

```
ScalingConfig = {
  metrics: {
    hitRate: { target: 0.85, weight: 0.4 },
    responseTime: { target: 50, weight: 0.3 },    // 50ms target
    cpuUsage: { target: 0.7, weight: 0.2 },
    memoryUsage: { target: 0.8, weight: 0.1 }
  },

  scalingThresholds: {
    scaleUp: 0.8,               // Scale up when composite score > 0.8
    scaleDown: 0.3              // Scale down when composite score < 0.3
  },

  minNodes: 3,
  maxNodes: 50,
  scaleUpCooldown: 300000,      // 5 minutes
  scaleDownCooldown: 600000,    // 10 minutes
```

```
  autoTuning: {
    enabled: true,
    learningWindow: 3600000,     // 1 hour
    adaptationRate: 0.1          // 10% adjustment per iteration
  }
}

class CacheAutoScaler:
  constructor(config):
    this.config = config
    this.metricsHistory = new TimeSeriesDB()
    this.lastScaleAction = Date.now()
    this.performanceModel = new PerformancePredictor()

  function evaluateScalingDecision():
    currentMetrics = this.collectCurrentMetrics()
    compositeScore = this.calculateCompositeScore(currentMetrics)

    scalingDecision = {
      action: 'none',
      reason: 'within_thresholds',
      confidence: 0,
      metrics: currentMetrics,
      compositeScore: compositeScore
    }

    // Check if scaling is needed
    if compositeScore > this.config.scalingThresholds.scaleUp:
      if this.canScaleUp():
        scalingDecision = this.generateScaleUpDecision(currentMetrics, compositeScore)
    else if compositeScore < this.config.scalingThresholds.scaleDown:
      if this.canScaleDown():
        scalingDecision = this.generateScaleDownDecision(currentMetrics, compositeScore)

    // Apply machine learning optimization if enabled
    if this.config.autoTuning.enabled:
      scalingDecision = this.optimizeWithML(scalingDecision)

    return scalingDecision

  function calculateCompositeScore(metrics):
    score = 0

    for [metricName, config] of Object.entries(this.config.metrics):
      metricValue = metrics[metricName]
```

```
    normalizedScore = this.normalizeMetric(metricName, metricValue, config.target)
    weightedScore = normalizedScore * config.weight
    score += weightedScore

  return Math.min(Math.max(score, 0), 1) // Clamp between 0 and 1

function normalizeMetric(metricName, value, target):
  switch metricName:
    case 'hitRate':
      // Lower hit rate = higher scaling need
      return Math.max(0, (target - value) / target)

    case 'responseTime':
      // Higher response time = higher scaling need
      return Math.max(0, (value - target) / target)

    case 'cpuUsage':
    case 'memoryUsage':
      // Higher usage = higher scaling need
      return Math.max(0, (value - target) / (1 - target))

    default:
      return 0

function generateScaleUpDecision(metrics, compositeScore):
  // Determine optimal number of nodes to add
  currentNodes = this.getCurrentNodeCount()
  predictedLoad = this.predictFutureLoad()

  // Calculate required capacity
  requiredCapacity = this.calculateRequiredCapacity(metrics, predictedLoad)
  optimalNodes = Math.ceil(requiredCapacity / this.getNodeCapacity())

  nodesToAdd = Math.min(
    optimalNodes - currentNodes,
    Math.ceil(currentNodes * 0.5), // Max 50% increase at once
    this.config.maxNodes - currentNodes
  )

  return {
    action: 'scale_up',
    reason: 'performance_degradation',
    confidence: compositeScore,
    nodesToAdd: nodesToAdd,
    targetNodes: currentNodes + nodesToAdd,
```

```
    predictedImprovement: this.predictPerformanceImprovement(nodesToAdd)
  }

function executeScalingDecision(decision):
  if decision.action === 'none':
    return { success: true, message: 'No scaling needed' }

  try:
    switch decision.action:
      case 'scale_up':
        return this.executeScaleUp(decision)
      case 'scale_down':
        return this.executeScaleDown(decision)
      case 'rebalance':
        return this.executeRebalance(decision)

  catch error:
    logScalingError(decision, error)
    return { success: false, error: error }

function executeScaleUp(decision):
  // Provision new cache nodes
  newNodes = []

  for i in range(decision.nodesToAdd):
    nodeConfig = this.generateOptimalNodeConfig()
    node = this.provisionCacheNode(nodeConfig)
    newNodes.push(node)

  // Wait for nodes to become ready
  readyNodes = await this.waitForNodesReady(newNodes)

  if readyNodes.length < decision.nodesToAdd:
    return {
      success: false,
      reason: 'node_provisioning_failed',
      readyNodes: readyNodes.length,
      expectedNodes: decision.nodesToAdd
    }

  // Add nodes to cluster
  for node in readyNodes:
    this.addNodeToCluster(node)

  // Trigger rebalancing
```

```
    this.triggerClusterRebalance()

    // Update scaling history
    this.recordScalingAction(decision)

    return {
      success: true,
      action: 'scale_up',
      nodesAdded: readyNodes.length,
      newClusterSize: this.getCurrentNodeCount()
    }
```

## Performance Optimizations

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### Memory Management

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**Memory Pool Optimization**:

```
MemoryConfig = {
  poolSizes: [64, 128, 256, 512, 1024, 2048, 4096], // Bytes
  preAllocatedPools: true,
  memoryCompaction: true,
  garbageCollectionThreshold: 0.9
}
```

### Network Optimization

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**Connection Pooling and Multiplexing**: - Persistent connections to reduce overhead - HTTP/2 multiplexing for parallel requests - Binary protocol for reduced bandwidth - Compression for large values

## Security Considerations

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### Cache Security Framework

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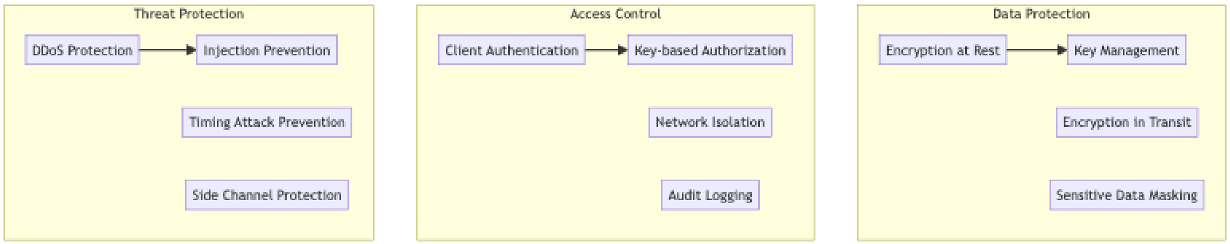


## Testing Strategy

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### Performance Testing

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**Load Testing Scenarios**: - Concurrent read/write operations (100K+ QPS) - Memory pressure testing - Network partition simulation - Cache warming performance

### Reliability Testing

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**Fault Tolerance Testing**: - Node failure scenarios - Split-brain prevention - Data consistency verification - Recovery time measurement

## Trade-offs and Considerations

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### Consistency vs Performance

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- **Strong consistency**: Data accuracy vs performance overhead
- **Eventual consistency**: Performance vs temporary inconsistency
- **Synchronous replication**: Consistency vs latency
- **Asynchronous replication**: Performance vs data loss risk

### Memory vs Network

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- **Large cache size**: Memory cost vs network reduction
- **Small cache size**: Network overhead vs memory efficiency
- **Compression**: CPU overhead vs memory/network savings
- **Serialization**: CPU cost vs network efficiency

### Scalability vs Complexity

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- **Auto-scaling**: Automatic optimization vs operational complexity
- **Manual scaling**: Predictable costs vs manual management
- **Sharding strategies**: Load distribution vs rebalancing overhead
- **Replication factor**: Fault tolerance vs storage cost

This distributed cache system provides a comprehensive foundation for high-performance caching with features like intelligent eviction, cache warming, multi-tier coherence, and auto-scaling while maintaining consistency, security, and operational efficiency standards.