Distributed File Storage System

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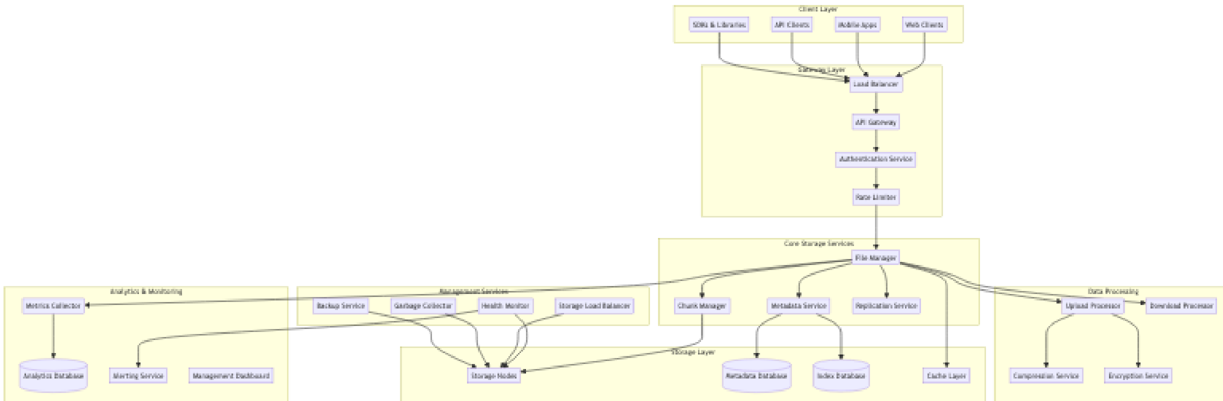

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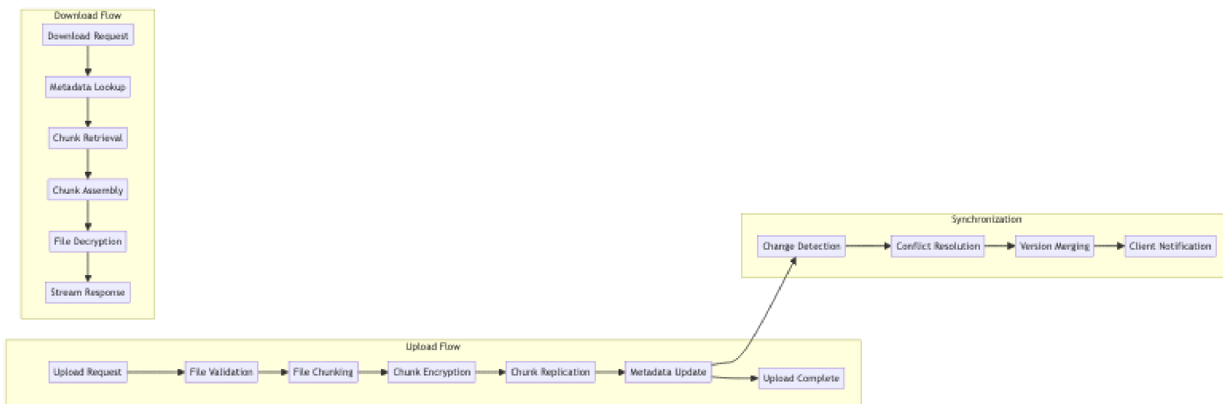

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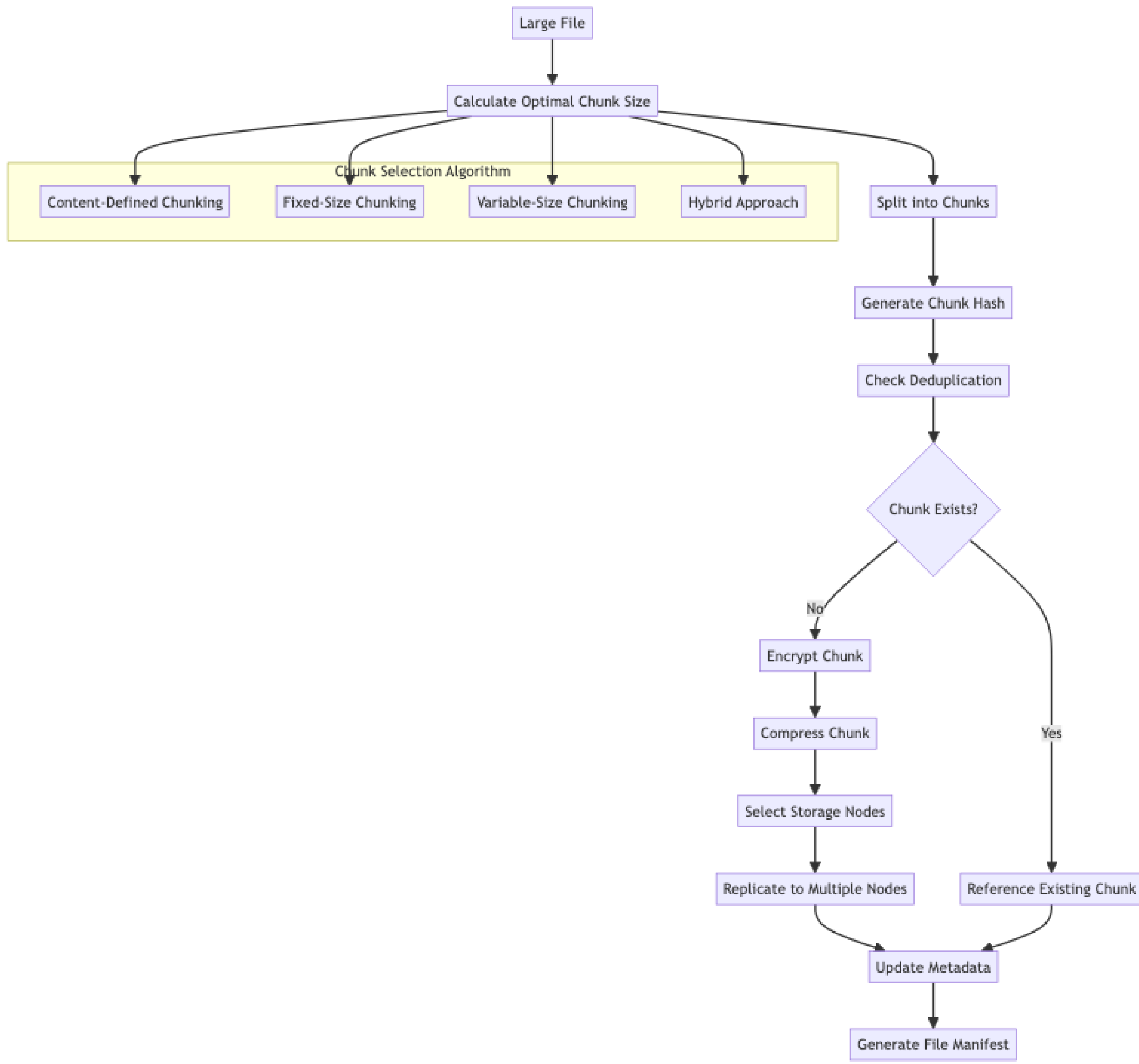

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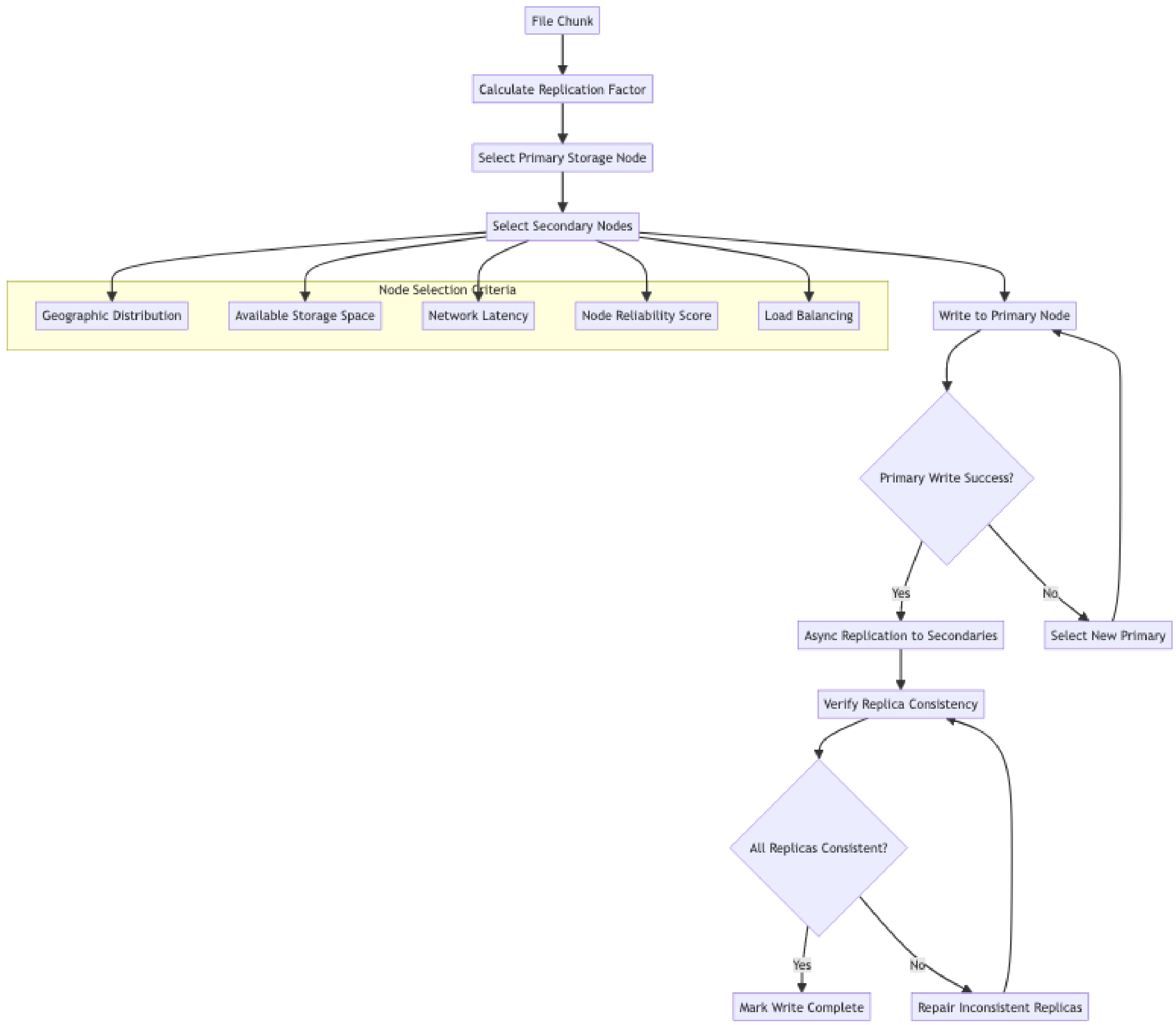

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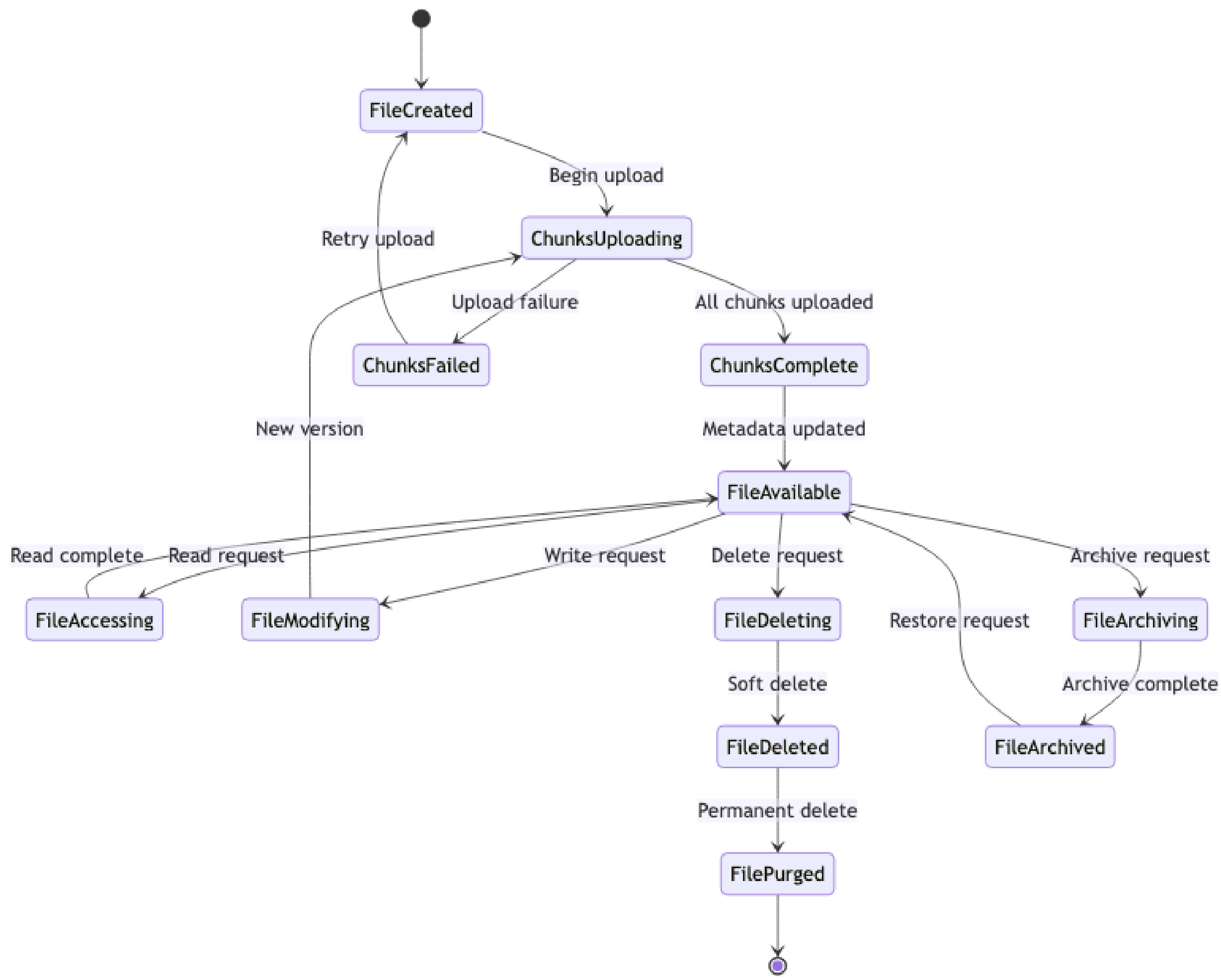

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1. Content-Defined Chunking Algorithm

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Purpose: Split files into variable-size chunks based on content patterns for optimal deduplication and efficient updates.

Rolling Hash Chunking:

```
ChunkingConfig = {
  minChunkSize: 262144,        // 256 KB minimum
  maxChunkSize: 16777216,      // 16 MB maximum
```

```
  targetChunkSize: 4194304,    // 4 MB target

  windowSize: 64,              // Rolling hash window
  hashPolynomial: 0x9E3779B1,  // Hash polynomial for Rabin fingerprinting

  boundary: {
    mask: 0x1FFF,              // 13-bit boundary mask (average 8KB chunks)
    threshold: 0x1000          // Boundary threshold
  }
}

function chunkFile(fileData):
  chunks = []
  chunkStart = 0
  position = 0
  rollingHash = 0

  // Initialize rolling hash window
  window = new CircularBuffer(ChunkingConfig.windowSize)

  while position < fileData.length:
    byte = fileData[position]

    // Update rolling hash using Rabin fingerprinting
    if window.isFull():
      oldByte = window.addAndGetEvicted(byte)
      rollingHash = updateRollingHash(rollingHash, oldByte, byte)
    else:
      window.add(byte)
      rollingHash = addToRollingHash(rollingHash, byte)

    // Check for chunk boundary
    currentChunkSize = position - chunkStart + 1

    isBoundary = (rollingHash & ChunkingConfig.boundary.mask) < ChunkingConfig.boundary.
    isMaxSize = currentChunkSize >= ChunkingConfig.maxChunkSize
    isEndOfFile = position === fileData.length - 1

    if (isBoundary and currentChunkSize >= ChunkingConfig.minChunkSize) or isMaxSize or
      // Create chunk
      chunkData = fileData.slice(chunkStart, position + 1)
      chunkHash = calculateChunkHash(chunkData)

      chunk = {
        id: generateChunkId(),
```

```
        hash: chunkHash,
        size: chunkData.length,
        offset: chunkStart,
        data: chunkData
      }

      chunks.push(chunk)
      chunkStart = position + 1

    position++

  return chunks

function updateRollingHash(hash, oldByte, newByte):
  // Remove contribution of old byte
  hash ^= powerTable[ChunkingConfig.windowSize - 1] * oldByte

  // Shift hash and add new byte
  hash = (hash << 1) ^ newByte

  return hash & 0xFFFFFFFF  // Keep as 32-bit value

function calculateChunkHash(chunkData):
  // Use SHA-256 for chunk content hashing
  return sha256(chunkData)
```

Deduplication Engine:

```
class DeduplicationEngine:
  constructor():
    this.chunkIndex = new Map()  // hash -> chunk metadata
    this.referenceCount = new Map()  // hash -> reference count
    this.bloomFilter = new BloomFilter(1000000, 3)  // For fast lookup

  function processChunk(chunk):
    chunkHash = chunk.hash

    // Quick bloom filter check
    if not this.bloomFilter.contains(chunkHash):
      // Definitely new chunk
      return this.storeNewChunk(chunk)

    // Check if chunk actually exists
    existingChunk = this.chunkIndex.get(chunkHash)

    if existingChunk:
```

```
      // Chunk exists - increment reference count
      this.referenceCount.set(chunkHash, this.referenceCount.get(chunkHash) + 1)

      return {
        isDuplicate: true,
        chunkId: existingChunk.id,
        savedBytes: chunk.size,
        referenceCount: this.referenceCount.get(chunkHash)
      }
    else:
      // False positive in bloom filter - store new chunk
      return this.storeNewChunk(chunk)

  function storeNewChunk(chunk):
    // Add to bloom filter
    this.bloomFilter.add(chunk.hash)

    // Store chunk metadata
    chunkMetadata = {
      id: chunk.id,
      hash: chunk.hash,
      size: chunk.size,
      createdAt: Date.now(),
      storageNodes: []
    }

    this.chunkIndex.set(chunk.hash, chunkMetadata)
    this.referenceCount.set(chunk.hash, 1)

    // Store actual chunk data
    storageResult = storeChunkData(chunk)
    chunkMetadata.storageNodes = storageResult.nodeIds

    return {
      isDuplicate: false,
      chunkId: chunk.id,
      storageNodes: storageResult.nodeIds
    }
```

2. Distributed Storage Node Selection Algorithm

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Purpose: Intelligently select storage nodes for data placement considering geography, load, reliability, and fault tolerance.

Multi-Criteria Node Selection:

```
NodeSelectionConfig = {
  replicationFactor: 3,           // Number of replicas
  minGeographicSpread: 2,         // Minimum different regions
  loadBalanceWeight: 0.3,         // Weight for load balancing
  reliabilityWeight: 0.4,         // Weight for node reliability
  latencyWeight: 0.2,             // Weight for network latency
  capacityWeight: 0.1,            // Weight for available capacity

  maxNodesPerRack: 1,            // Fault tolerance: max 1 node per rack
  maxNodesPerDatacenter: 2,      // Fault tolerance: max 2 nodes per DC
  excludeFailedNodes: true        // Exclude recently failed nodes
}

function selectStorageNodes(fileSize, clientLocation, excludeNodes = []):
  availableNodes = getAvailableStorageNodes()

  // Filter out excluded and unhealthy nodes
  candidateNodes = availableNodes.filter(node =>
    not excludeNodes.includes(node.id) and
    node.isHealthy and
    node.availableSpace >= fileSize
  )

  if candidateNodes.length < NodeSelectionConfig.replicationFactor:
    throw new Error('Insufficient healthy storage nodes available')

  // Score all candidate nodes
  scoredNodes = candidateNodes.map(node => ({
    node: node,
    score: calculateNodeScore(node, clientLocation, fileSize)
  }))

  // Sort by score (descending)
  rankedNodes = scoredNodes.sort((a, b) => b.score - a.score)

  // Select nodes with geographic and fault tolerance constraints
  selectedNodes = selectWithConstraints(rankedNodes, NodeSelectionConfig.replicationFact

  return selectedNodes.map(scored => scored.node)

function calculateNodeScore(node, clientLocation, fileSize):
  score = 0
```

```
  // Load balancing factor
  loadScore = 1 - (node.currentLoad / node.maxCapacity)
  score += loadScore * NodeSelectionConfig.loadBalanceWeight

  // Reliability factor
  reliabilityScore = calculateReliabilityScore(node)
  score += reliabilityScore * NodeSelectionConfig.reliabilityWeight

  // Latency factor
  latencyScore = calculateLatencyScore(node, clientLocation)
  score += latencyScore * NodeSelectionConfig.latencyWeight

  // Capacity factor
  capacityScore = node.availableSpace / node.totalCapacity
  score += capacityScore * NodeSelectionConfig.capacityWeight

  return score

function selectWithConstraints(rankedNodes, targetCount):
  selectedNodes = []
  usedRacks = new Set()
  usedDatacenters = new Map()  // datacenter -> count
  usedRegions = new Set()

  for scoredNode in rankedNodes:
    node = scoredNode.node

    // Check rack constraint
    if usedRacks.has(node.rackId) and NodeSelectionConfig.maxNodesPerRack === 1:
      continue

    // Check datacenter constraint
    dcCount = usedDatacenters.get(node.datacenterId) || 0
    if dcCount >= NodeSelectionConfig.maxNodesPerDatacenter:
      continue

    // Add node to selection
    selectedNodes.push(scoredNode)
    usedRacks.add(node.rackId)
    usedDatacenters.set(node.datacenterId, dcCount + 1)
    usedRegions.add(node.regionId)

    if selectedNodes.length === targetCount:
      break
```

```
  // Verify geographic spread requirement
  if usedRegions.size < NodeSelectionConfig.minGeographicSpread:
    throw new Error('Cannot satisfy minimum geographic spread requirement')

  return selectedNodes

function calculateReliabilityScore(node):
  // Calculate based on historical uptime and performance
  uptimeScore = node.uptimePercentage / 100
  performanceScore = 1 - (node.averageErrorRate)
  maintenanceScore = 1 - (node.scheduledMaintenanceRatio)

  return (uptimeScore * 0.5 + performanceScore * 0.3 + maintenanceScore * 0.2)
```

3. Consistency and Conflict Resolution Algorithm

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Purpose: Maintain data consistency across distributed replicas and resolve conflicts in concurrent modifications.

Vector Clock-Based Versioning:

```
ConflictResolutionConfig = {
  conflictResolutionStrategy: 'last_writer_wins', // 'manual', 'merge', 'last_writer_win
  maxVersionHistory: 10,       // Keep last 10 versions
  conflictDetectionEnabled: true,
  automaticMergeEnabled: false
}

class VectorClock:
  constructor(nodeId):
    this.nodeId = nodeId
    this.clock = new Map()  // nodeId -> timestamp

  function increment():
    currentTime = Date.now()
    this.clock.set(this.nodeId, currentTime)
    return this

  function update(otherClock):
    for [nodeId, timestamp] of otherClock.clock:
      ourTimestamp = this.clock.get(nodeId) || 0
      this.clock.set(nodeId, Math.max(ourTimestamp, timestamp))
```

```
    // Increment our own timestamp
    this.increment()
    return this

  function compare(otherClock):
    // Returns: 'before', 'after', 'concurrent', or 'equal'

    let hasSmaller = false
    let hasLarger = false

    // Check all timestamps in both clocks
    allNodes = new Set([...this.clock.keys(), ...otherClock.clock.keys()])

    for nodeId of allNodes:
      ourTime = this.clock.get(nodeId) || 0
      theirTime = otherClock.clock.get(nodeId) || 0

      if ourTime < theirTime:
        hasSmaller = true
      else if ourTime > theirTime:
        hasLarger = true

    if hasSmaller and hasLarger:
      return 'concurrent'
    else if hasSmaller:
      return 'before'
    else if hasLarger:
      return 'after'
    else:
      return 'equal'

function resolveFileConflict(localVersion, remoteVersion):
  comparison = localVersion.vectorClock.compare(remoteVersion.vectorClock)

  switch comparison:
    case 'before':
      // Remote version is newer - accept it
      return {
        resolution: 'accept_remote',
        winningVersion: remoteVersion,
        conflictDetected: false
      }

    case 'after':
```

```
      // Local version is newer - keep it
      return {
        resolution: 'keep_local',
        winningVersion: localVersion,
        conflictDetected: false
      }

    case 'equal':
      // Identical versions - no conflict
      return {
        resolution: 'no_change',
        winningVersion: localVersion,
        conflictDetected: false
      }

    case 'concurrent':
      // Conflict detected - apply resolution strategy
      return resolveConcurrentConflict(localVersion, remoteVersion)

function resolveConcurrentConflict(localVersion, remoteVersion):
  conflict = {
    localVersion: localVersion,
    remoteVersion: remoteVersion,
    conflictType: detectConflictType(localVersion, remoteVersion),
    detectedAt: Date.now()
  }

  switch ConflictResolutionConfig.conflictResolutionStrategy:
    case 'last_writer_wins':
      return resolveByLastWriter(conflict)

    case 'manual':
      return createManualResolutionTask(conflict)

    case 'merge':
      return attemptAutomaticMerge(conflict)

    default:
      return resolveByLastWriter(conflict)

function resolveByLastWriter(conflict):
  localTime = conflict.localVersion.lastModified
  remoteTime = conflict.remoteVersion.lastModified

  if remoteTime > localTime:
```

```
    winningVersion = conflict.remoteVersion
    resolution = 'accept_remote'
  else:
    winningVersion = conflict.localVersion
    resolution = 'keep_local'

  // Store conflict information for audit
  logConflictResolution(conflict, resolution)

  return {
    resolution: resolution,
    winningVersion: winningVersion,
    conflictDetected: true,
    conflictInfo: conflict
  }
```

4. Erasure Coding for Fault Tolerance

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Purpose: Provide data protection and storage efficiency using erasure coding instead of simple replication.

Reed-Solomon Erasure Coding:

```
ErasureCodeConfig = {
  dataShards: 6,              // Number of data shards
  parityShards: 3,            // Number of parity shards
  totalShards: 9,             // Total shards (data + parity)
  minShardsForRecovery: 6,    // Minimum shards needed to reconstruct

  shardSize: 1048576,         // 1 MB per shard
  maxConcurrentReconstructions: 5,
  reconstructionTimeout: 30000  // 30 seconds
}

class ErasureCoder:
  constructor(config):
    this.config = config
    this.encoder = new ReedSolomonEncoder(config.dataShards, config.parityShards)

  function encodeFile(fileData):
    // Pad file to multiple of shard size if necessary
    paddedData = padToShardBoundary(fileData)
```

```
  // Split into chunks that can be encoded
  chunks = splitIntoEncodableChunks(paddedData)

  encodedChunks = []

  for chunk in chunks:
    // Split chunk into data shards
    dataShards = splitIntoDataShards(chunk)

    // Generate parity shards
    parityShards = this.encoder.generateParityShards(dataShards)

    // Create shard metadata
    shardSet = {
      chunkId: generateChunkId(),
      dataShards: dataShards.map((shard, index) => ({
        shardId: generateShardId(),
        index: index,
        data: shard,
        isDataShard: true
      })),
      parityShards: parityShards.map((shard, index) => ({
        shardId: generateShardId(),
        index: index + this.config.dataShards,
        data: shard,
        isDataShard: false
      }))
    }

    encodedChunks.push(shardSet)

  return {
    originalSize: fileData.length,
    paddedSize: paddedData.length,
    chunks: encodedChunks,
    encodingParams: {
      dataShards: this.config.dataShards,
      parityShards: this.config.parityShards,
      shardSize: this.config.shardSize
    }
  }

function decodeFile(encodedFile, availableShards):
  decodedChunks = []
```

```
  for chunkInfo in encodedFile.chunks:
    // Collect available shards for this chunk
    chunkShards = availableShards.filter(shard => shard.chunkId === chunkInfo.chunkId)

    if chunkShards.length < this.config.minShardsForRecovery:
      throw new Error(`Insufficient shards for chunk ${chunkInfo.chunkId}: ${chunkShar

    // Decode chunk
    decodedChunk = this.decodeChunk(chunkShards)
    decodedChunks.push(decodedChunk)

  // Reassemble file
  reassembledData = concatenateChunks(decodedChunks)

  // Remove padding
  originalData = removePadding(reassembledData, encodedFile.originalSize)

  return originalData

function decodeChunk(availableShards):
  // Sort shards by index
  sortedShards = availableShards.sort((a, b) => a.index - b.index)

  // Check if we have enough shards
  if sortedShards.length < this.config.minShardsForRecovery:
    throw new Error('Insufficient shards for reconstruction')

  // If we have all data shards, no reconstruction needed
  dataShards = sortedShards.filter(shard => shard.isDataShard)

  if dataShards.length === this.config.dataShards:
    return reassembleFromDataShards(dataShards)

  // Reconstruction needed
  return this.reconstructChunk(sortedShards)

function reconstructChunk(availableShards):
  // Use Reed-Solomon decoder to reconstruct missing shards
  reconstructedShards = this.encoder.reconstruct(
    availableShards,
    this.config.dataShards,
    this.config.parityShards
  )

  // Extract only the data shards
```

```
    dataShards = reconstructedShards.slice(0, this.config.dataShards)

    return reassembleFromDataShards(dataShards)
```

Proactive Reconstruction:

```
function monitorShardHealth():
  // Check health of all stored shards
  unhealthyShards = identifyUnhealthyShards()

  for shard in unhealthyShards:
    if shouldTriggerReconstruction(shard):
      scheduleShardReconstruction(shard)

function scheduleShardReconstruction(shard):
  reconstructionTask = {
    shardId: shard.id,
    chunkId: shard.chunkId,
    priority: calculateReconstructionPriority(shard),
    createdAt: Date.now()
  }

  addToReconstructionQueue(reconstructionTask)

function calculateReconstructionPriority(shard):
  // Higher priority for:
  // - Chunks with fewer available shards
  // - Recently accessed files
  // - Critical system files

  chunkInfo = getChunkInfo(shard.chunkId)
  availableShards = countAvailableShards(shard.chunkId)

  priority = 0

  // Urgency based on remaining shards
  remainingShards = availableShards - 1 // Excluding the failed shard
  if remainingShards <= ErasureCodeConfig.minShardsForRecovery:
    priority += 1000 // Critical priority
  else if remainingShards <= ErasureCodeConfig.minShardsForRecovery + 1:
    priority += 500 // High priority
  else:
    priority += 100 // Normal priority

  // Access pattern boost
  if chunkInfo.lastAccessTime > Date.now() - 86400000: // Last 24 hours
```

```
    priority += 50

  return priority
```

5. Intelligent Caching Strategy

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Purpose: Optimize file access performance through multi-tiered caching with predictive prefetching and intelligent eviction.

Multi-Tier Cache Architecture:

```
CacheConfig = {
  tiers: {
    memory: {
      maxSize: 1073741824,      // 1 GB
      ttl: 3600000,             // 1 hour
      evictionPolicy: 'lru'
    },
    ssd: {
      maxSize: 107374182400,    // 100 GB
      ttl: 86400000,            // 24 hours
      evictionPolicy: 'lfu'
    },
    nearline: {
      maxSize: 1099511627776,   // 1 TB
      ttl: 604800000,           // 7 days
      evictionPolicy: 'aged_lru'
    }
  },

  prefetchEnabled: true,
  compressionEnabled: true,
  encryptionEnabled: true
}

class IntelligentCache:
  constructor(config):
    this.config = config
    this.memoryCache = new LRUCache(config.tiers.memory)
    this.ssdCache = new LFUCache(config.tiers.ssd)
    this.nearlineCache = new AgedLRUCache(config.tiers.nearline)
    this.accessPredictor = new AccessPredictor()
```

```
function get(fileId):
  // Try memory cache first
  cached = this.memoryCache.get(fileId)
  if cached:
    this.recordCacheHit('memory', fileId)
    return cached

  // Try SSD cache
  cached = this.ssdCache.get(fileId)
  if cached:
    this.recordCacheHit('ssd', fileId)
    // Promote to memory cache
    this.memoryCache.put(fileId, cached)
    return cached

  // Try nearline cache
  cached = this.nearlineCache.get(fileId)
  if cached:
    this.recordCacheHit('nearline', fileId)
    // Promote to SSD cache
    this.ssdCache.put(fileId, cached)
    return cached

  // Cache miss - need to fetch from storage
  this.recordCacheMiss(fileId)
  return null

function put(fileId, fileData, metadata):
  // Determine initial cache tier based on file characteristics
  tier = this.selectInitialTier(fileData, metadata)

  // Cache in selected tier and all faster tiers
  switch tier:
    case 'nearline':
      this.nearlineCache.put(fileId, fileData)
      break
    case 'ssd':
      this.ssdCache.put(fileId, fileData)
      this.nearlineCache.put(fileId, fileData)
      break
    case 'memory':
      this.memoryCache.put(fileId, fileData)
      this.ssdCache.put(fileId, fileData)
      this.nearlineCache.put(fileId, fileData)
      break
```

```
  // Update access predictor
  this.accessPredictor.recordAccess(fileId, metadata)

  // Trigger prefetching if enabled
  if this.config.prefetchEnabled:
    this.triggerPrefetch(fileId, metadata)

function selectInitialTier(fileData, metadata):
  score = 0

  // File size factor - smaller files go to faster tiers
  if fileData.length < 1048576: // < 1MB
    score += 30
  else if fileData.length < 10485760: // < 10MB
    score += 20
  else if fileData.length < 104857600: // < 100MB
    score += 10

  // Access frequency factor
  if metadata.accessCount > 100:
    score += 25
  else if metadata.accessCount > 10:
    score += 15
  else if metadata.accessCount > 1:
    score += 5

  // Recency factor
  hoursSinceAccess = (Date.now() - metadata.lastAccess) / 3600000
  if hoursSinceAccess < 1:
    score += 20
  else if hoursSinceAccess < 24:
    score += 10
  else if hoursSinceAccess < 168: // 1 week
    score += 5

  // File type factor
  if metadata.fileType in ['image', 'video', 'document']:
    score += 10

  // Select tier based on score
  if score >= 60:
    return 'memory'
  else if score >= 30:
    return 'ssd'
```

```
    else:
      return 'nearline'

  function triggerPrefetch(fileId, metadata):
    // Predict related files that might be accessed soon
    relatedFiles = this.accessPredictor.predictRelatedFiles(fileId, metadata)

    for relatedFileId in relatedFiles:
      if not this.hasInAnyTier(relatedFileId):
        // Schedule background prefetch
        this.schedulePrefetch(relatedFileId)
```

Performance Optimizations

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Parallel Processing

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Concurrent Upload/Download:

```
ParallelConfig = {
  maxConcurrentChunks: 10,
  chunkUploadTimeout: 30000,
  connectionPoolSize: 20,
  retryAttempts: 3
}
```

Compression Strategy

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Adaptive Compression: - Text files: gzip/deflate compression - Images: conditional compression based on format - Videos: minimal compression (already compressed) - Binary files: lz4 for speed vs size balance

Security Considerations

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Data Protection Framework

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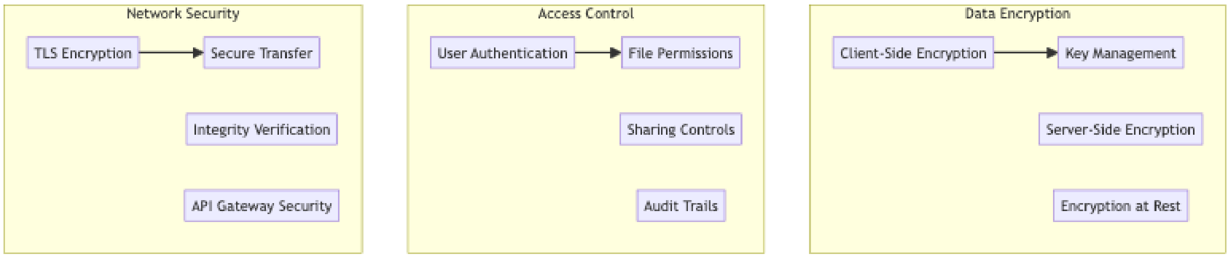

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Fault Tolerance Testing

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Failure Scenarios: - Node failure simulation - Network partition testing - Data corruption detection - Recovery time measurement

Performance Testing

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Load Testing Scenarios: - Concurrent file operations (10K+ users) - Large file handling (multi-GB files) - High-frequency small file operations - Network bandwidth optimization

Trade-offs and Considerations

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Consistency vs Availability

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- **Strong consistency**: Data accuracy vs system availability
- **Eventual consistency**: Performance vs immediate consistency
- **Replication strategies**: Storage cost vs fault tolerance
- **Conflict resolution**: Automatic vs manual resolution

Storage vs Performance

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- **Erasure coding**: Storage efficiency vs reconstruction overhead
- **Compression**: Space savings vs CPU usage
- **Caching strategies**: Memory usage vs access speed
- **Chunk size optimization**: Deduplication efficiency vs metadata overhead

Security vs Usability

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- **Encryption overhead**: Security vs performance impact
- **Key management**: Security vs operational complexity
- **Access controls**: Security vs user convenience
- **Audit requirements**: Compliance vs storage costs

This distributed file storage system provides a comprehensive foundation for scalable, reliable file management with features like intelligent chunking, erasure coding, multi-tier caching, and robust security while maintaining high performance, fault tolerance, and storage efficiency standards.