URL Shortener Service (bit.ly/tinyurl)

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- Testing Strategy
  - Performance Testing
  - Security Testing
- Trade-offs and Considerations
  - Performance vs Accuracy
  - Scalability vs Cost
  - Security vs Usability

Requirements Gathering

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Functional Requirements

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Core URL Shortening Features: - Shorten long URLs to 6-8 character codes - Redirect users from short URLs to original URLs - Custom aliases for branded short URLs - Bulk URL shortening via API - URL expiration dates and auto-deletion - QR code generation for short URLs - URL preview before redirect (optional) - Click tracking and analytics

User Management: - Anonymous URL shortening (basic) - User registration for advanced features - Dashboard to manage shortened URLs - URL history and favorites - Team/organization accounts - API key management for developers

Analytics & Monitoring: - Click count tracking - Geographic location analytics - Referrer tracking - Device and browser analytics - Real-time analytics dashboard - Export analytics data

Non-Functional Requirements

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Performance: - Redirect latency < 10ms for cached URLs - Support 1 billion URLs in the system - Handle 100 million redirects per day - 99.99% uptime SLA - Global CDN for fast redirects

Scalability: - Horizontal scaling of all services - Handle 10,000 requests per second - Auto-scaling based on traffic patterns - Support for viral content traffic spikes

Security: - Protection against malicious URLs - Rate limiting to prevent abuse - CAPTCHA for bulk operations - DDoS protection - SSL/TLS for all connections

Reliability: - No data loss for shortened URLs - Automatic failover and backup - Data replication across regions - Circuit breaker patterns

Traffic Estimation & Capacity Planning

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User Base Analysis

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- **Daily Active Users:** 10 million users
- **Anonymous Users:** 80% of total traffic
- **Registered Users:** 2 million users
- **URLs Shortened per Day:** 5 million URLs
- **Redirects per Day:** 100 million redirects
- **Read:Write Ratio:** 20:1 (heavy read workload)

Traffic Calculations

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URL Operations:

```
URL Shortening:
- Daily URL creations = 5M URLs/day
- Peak creation rate = 5M × 3 / (24 × 3600) = 174 URLs/sec
- Storage per URL = 500 bytes (URL + metadata)
- Daily storage growth = 5M × 500B = 2.5GB/day

URL Redirects:
- Daily redirects = 100M redirects/day
- Peak redirect rate = 100M × 3 / (24 × 3600) = 3,472 redirects/sec
- Average redirect rate = 100M / (24 × 3600) = 1,157 redirects/sec
```

Storage Requirements:

```
URL Database:
- URLs after 5 years = 5M × 365 × 5 = 9.125B URLs
- Storage per URL = 500 bytes
- Total storage = 9.125B × 500B = 4.56TB
- With indexing overhead (3x) = 13.7TB

Analytics Database:
- Click events per day = 100M
- Storage per event = 200 bytes
- Daily analytics storage = 100M × 200B = 20GB/day
- Annual analytics storage = 20GB × 365 = 7.3TB
```

Cache Requirements:

```
Redis Cache (Hot URLs):
- Hot URLs (20% of traffic) = 20M URLs in cache
- Cache entry size = 200 bytes (short_url -> long_url)
- Total cache memory = 20M × 200B = 4GB
- With overhead and redundancy = 12GB total
```

Infrastructure Sizing:

```
Application Servers:
- URL shortening service: 5 servers
- Redirect service: 20 servers (read-heavy)
- Analytics service: 3 servers

Database Requirements:
- URL database: 3 shards, 16GB RAM each
- Analytics database: 5 shards, 32GB RAM each
- Cache layer: 3 Redis nodes, 8GB each

CDN Requirements:
- Global CDN for redirect service
- Cache TTL: 1 hour for popular URLs
- Bandwidth: 1GB/s peak
```

Database Schema Design

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URL Database Schema

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```sql
-- Shortened URLs table
CREATE TABLE shortened_urls (
    id BIGINT PRIMARY KEY AUTO_INCREMENT,
    short_code VARCHAR(10) UNIQUE NOT NULL,
    original_url TEXT NOT NULL,
    user_id BIGINT NULL, -- NULL for anonymous users
    custom_alias VARCHAR(50) NULL,
    title VARCHAR(255),
    description TEXT,
    created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
    expires_at TIMESTAMP NULL,
    is_active BOOLEAN DEFAULT TRUE,
    click_count BIGINT DEFAULT 0,
    last_accessed TIMESTAMP NULL,

    INDEX idx_short_code (short_code),
    INDEX idx_user_id (user_id),
    INDEX idx_created_at (created_at),
    INDEX idx_expires_at (expires_at),
    FOREIGN KEY (user_id) REFERENCES users(user_id)
);

-- Users table
CREATE TABLE users (
    user_id BIGINT PRIMARY KEY AUTO_INCREMENT,
    username VARCHAR(50) UNIQUE NOT NULL,
    email VARCHAR(255) UNIQUE NOT NULL,
    password_hash VARCHAR(255) NOT NULL,
    api_key VARCHAR(64) UNIQUE,
    subscription_type ENUM('free', 'premium', 'enterprise') DEFAULT 'free',
    created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
    last_login TIMESTAMP,
    is_active BOOLEAN DEFAULT TRUE,

    INDEX idx_username (username),
    INDEX idx_email (email),
    INDEX idx_api_key (api_key)
);

-- Custom domains for branded URLs
CREATE TABLE custom_domains (
    domain_id BIGINT PRIMARY KEY AUTO_INCREMENT,
    user_id BIGINT NOT NULL,
    domain_name VARCHAR(255) UNIQUE NOT NULL,
    is_verified BOOLEAN DEFAULT FALSE,
    created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
    INDEX idx_user_id (user_id),
    INDEX idx_domain_name (domain_name),
    FOREIGN KEY (user_id) REFERENCES users(user_id)
);
```

Analytics Database Schema

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```
-- Click events table (partitioned by date)
CREATE TABLE click_events (
    event_id BIGINT PRIMARY KEY AUTO_INCREMENT,
    short_code VARCHAR(10) NOT NULL,
    ip_address VARCHAR(45),
    user_agent TEXT,
    referer TEXT,
    country VARCHAR(2),
    city VARCHAR(100),
    device_type ENUM('mobile', 'desktop', 'tablet', 'other'),
    browser VARCHAR(50),
    os VARCHAR(50),
    clicked_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,

    INDEX idx_short_code (short_code),
    INDEX idx_clicked_at (clicked_at),
    INDEX idx_country (country),
    INDEX idx_device_type (device_type)
) PARTITION BY RANGE (YEAR(clicked_at)) (
    PARTITION p2024 VALUES LESS THAN (2025),
    PARTITION p2025 VALUES LESS THAN (2026),
    PARTITION p2026 VALUES LESS THAN (2027)
);

-- Daily aggregated statistics
CREATE TABLE daily_stats (
    stat_id BIGINT PRIMARY KEY AUTO_INCREMENT,
    short_code VARCHAR(10) NOT NULL,
    stat_date DATE NOT NULL,
    click_count INT DEFAULT 0,
    unique_visitors INT DEFAULT 0,
    top_country VARCHAR(2),
    top_referer VARCHAR(255),

    UNIQUE KEY unique_url_date (short_code, stat_date),
    INDEX idx_stat_date (stat_date)
);
```

Sample API Endpoints

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URL Shortening APIs

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```
POST /api/v1/urls/shorten
Content-Type: application/json
Authorization: Bearer <api_key> (optional)

{
    "url": "https://www.example.com/very/long/url/with/many/parameters?param1=value1&par
    "custom_alias": "my-link", // optional
    "expires_at": "2024-12-31T23:59:59Z", // optional
    "title": "Example Website" // optional
}

Response (201 Created):
{
    "success": true,
    "data": {
        "short_url": "https://short.ly/abc123",
        "short_code": "abc123",
        "original_url": "https://www.example.com/very/long/url/with/many/parameters?para
        "qr_code": "https://api.short.ly/qr/abc123.png",
        "created_at": "2024-01-15T10:30:00Z",
        "expires_at": "2024-12-31T23:59:59Z"
    }
}
```

```
GET /api/v1/urls/{short_code}
Authorization: Bearer <api_key>

Response (200 OK):
{
    "success": true,
    "data": {
        "short_code": "abc123",
        "original_url": "https://www.example.com/very/long/url/with/many/parameters?para
        "title": "Example Website",
        "created_at": "2024-01-15T10:30:00Z",
        "expires_at": "2024-12-31T23:59:59Z",
        "click_count": 1247,
        "is_active": true
    }
}
```

Redirect API

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```
GET /{short_code}
User-Agent: Mozilla/5.0...
X-Forwarded-For: 192.168.1.1

Response (302 Found):
Location: https://www.example.com/very/long/url/with/many/parameters?param1=value1&param
Cache-Control: public, max-age=3600

// Analytics event is logged asynchronously
```

Analytics APIs

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```
GET /api/v1/urls/{short_code}/analytics?period=7d
Authorization: Bearer <api_key>

Response (200 OK):
{
    "success": true,
    "data": {
        "short_code": "abc123",
        "period": "7d",
        "total_clicks": 1247,
        "unique_visitors": 892,
        "daily_stats": [
            {
                "date": "2024-01-15",
                "clicks": 234,
                "unique_visitors": 178
            }
        ],
        "top_countries": [
            {"country": "US", "clicks": 456, "percentage": 36.6},
            {"country": "UK", "clicks": 234, "percentage": 18.8}
        ],
        "top_referrers": [
            {"referrer": "google.com", "clicks": 345},
            {"referrer": "facebook.com", "clicks": 123}
        ],
        "devices": {
            "mobile": {"clicks": 623, "percentage": 50.0},
            "desktop": {"clicks": 498, "percentage": 39.9},
            "tablet": {"clicks": 126, "percentage": 10.1}
        }
    }
}
```

Bulk Operations APIs

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```
POST /api/v1/urls/bulk
Authorization: Bearer <api_key>
Content-Type: application/json

{
    "urls": [
        {
            "url": "https://example1.com/long-url-1",
            "custom_alias": "link1"
        },
        {
            "url": "https://example2.com/long-url-2",
            "expires_at": "2024-12-31T23:59:59Z"
        }
    ]
}

Response (201 Created):
{
    "success": true,
    "data": {
        "created_urls": [
            {
                "short_url": "https://short.ly/link1",
                "original_url": "https://example1.com/long-url-1"
            },
            {
                "short_url": "https://short.ly/def456",
                "original_url": "https://example2.com/long-url-2"
            }
        ],
        "failed_urls": []
    }
}
```

High-Level Design (HLD)

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System Architecture Overview

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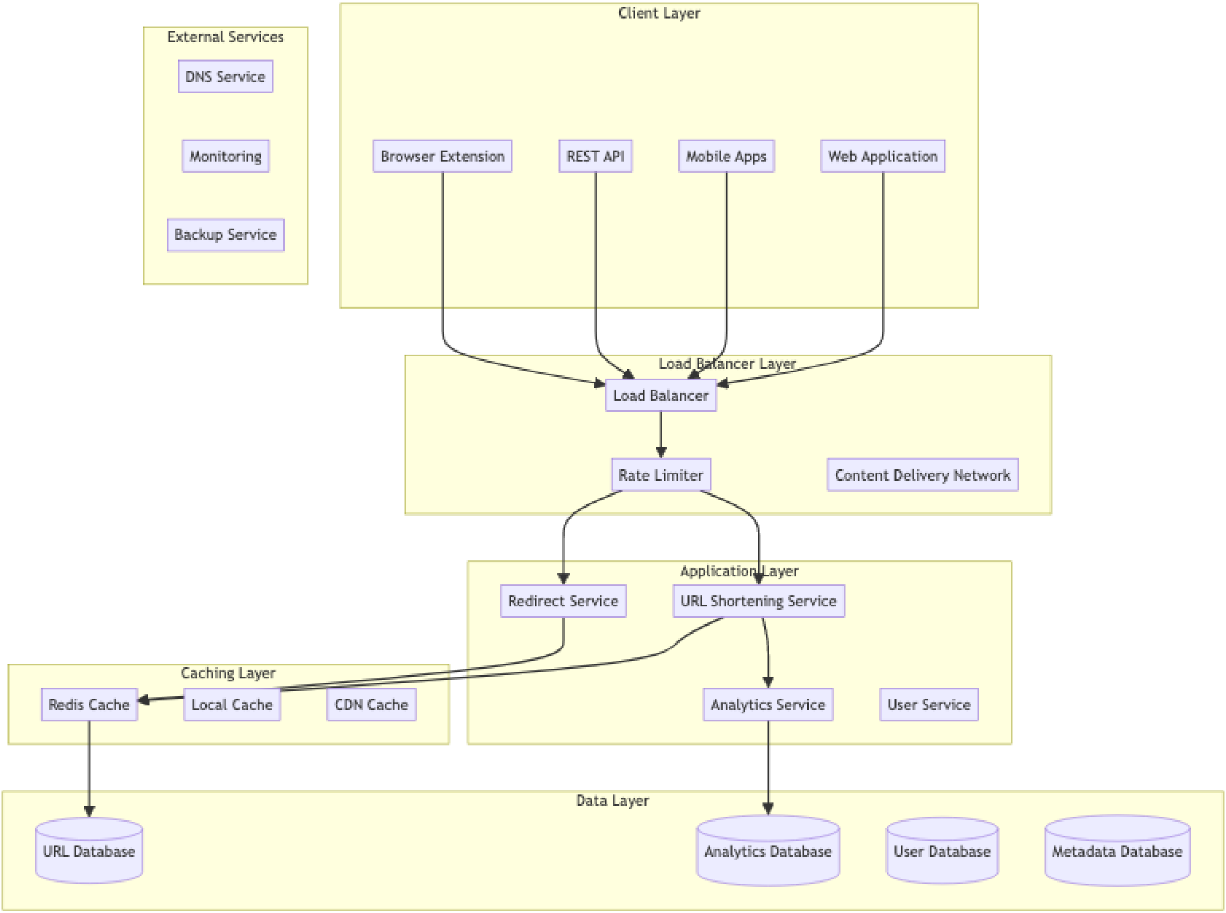

URL Shortening Data Flow

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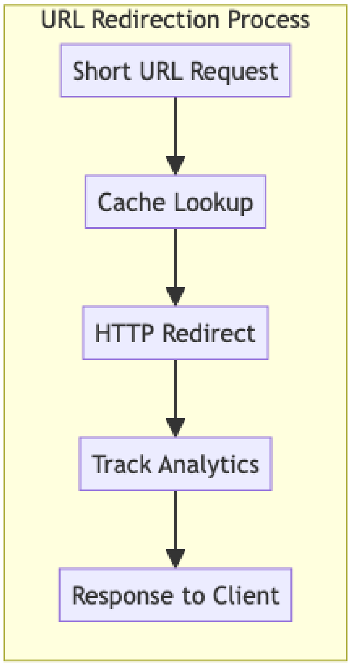
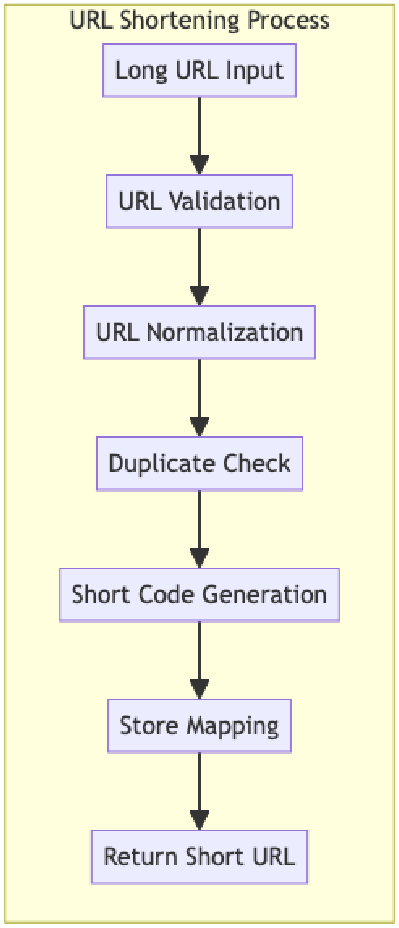

URL Redirection Process
Short URL Request
Cache Lookup
HTTP Redirect
Track Analytics
Response to Client


URL Shortening Process
Long URL Input
URL Validation
URL Normalization
Duplicate Check
Short Code Generation
Store Mapping
Return Short URL

Low-Level Design (LLD)

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URL Encoding Algorithm Flow

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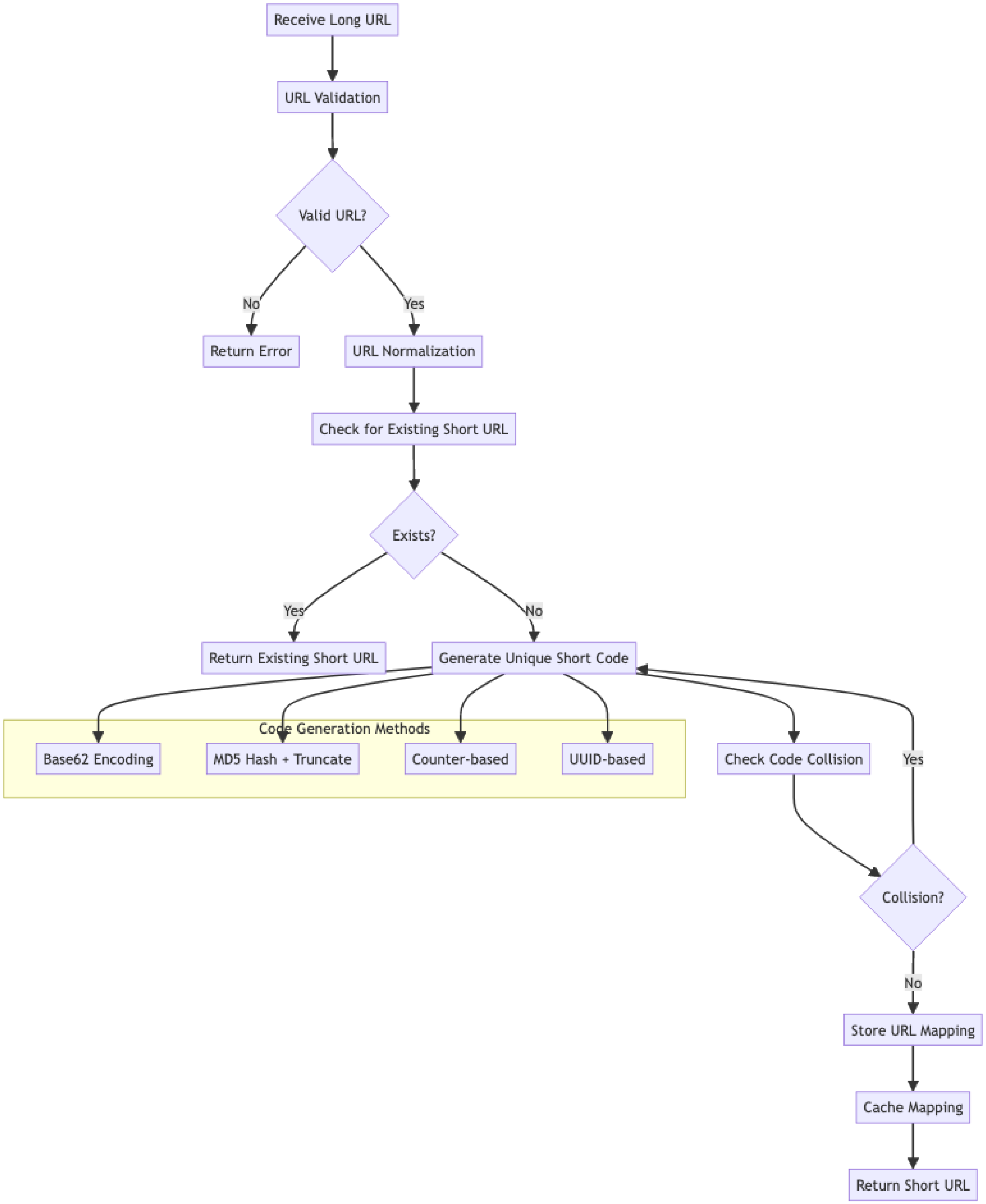

URL Redirection Flow

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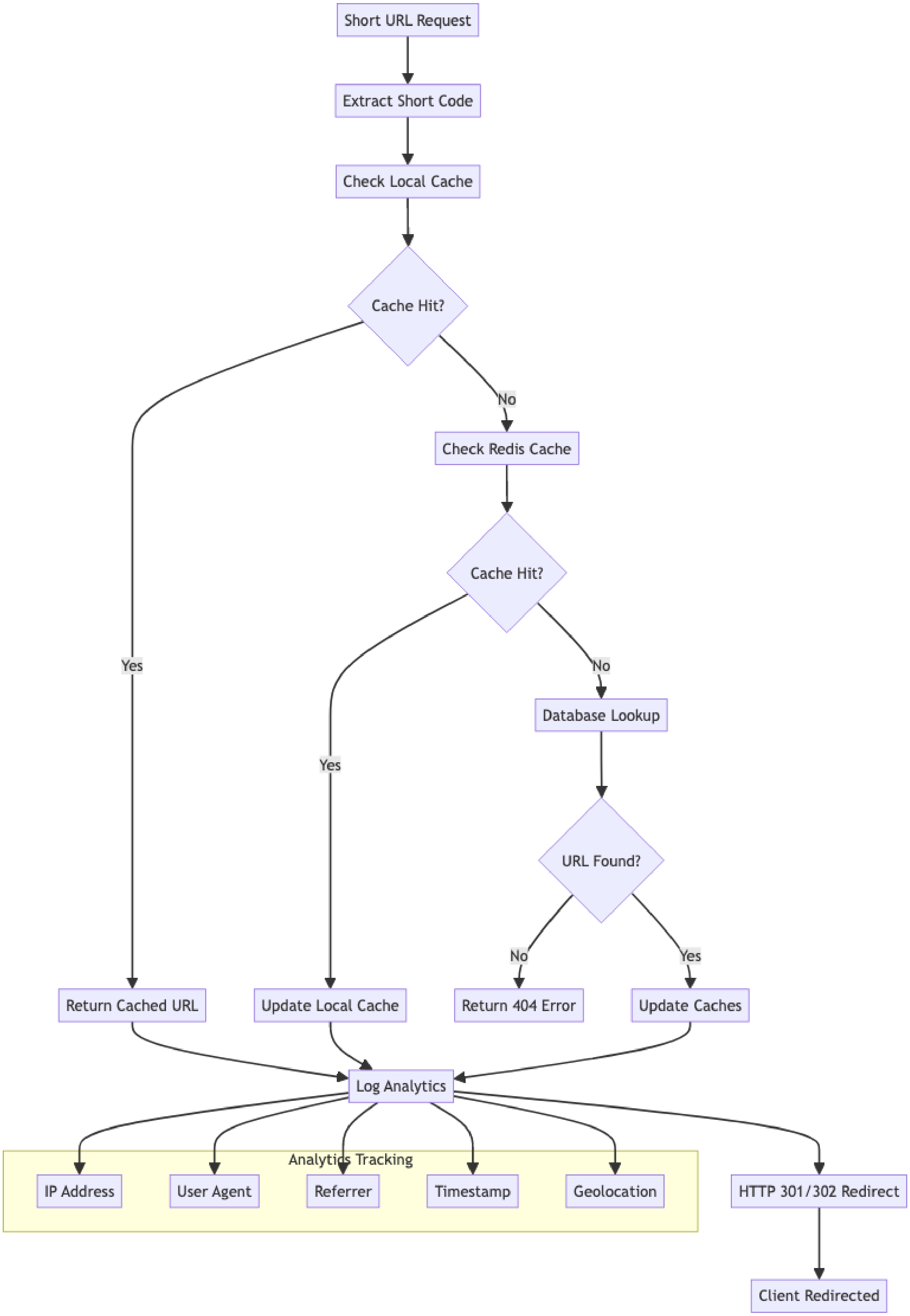
Short URL Request
Extract Short Code
Check Local Cache
Cache Hit?
Yes
No
Check Redis Cache
Cache Hit?
Yes
No
Database Lookup
URL Found?
No
Yes
Return Cached URL
Update Local Cache
Return 404 Error
Update Caches
Log Analytics
Analytics Tracking
IP Address
User Agent
Referrer
Timestamp
Geolocation
HTTP 301/302 Redirect
Client Redirected

Database Sharding Strategy

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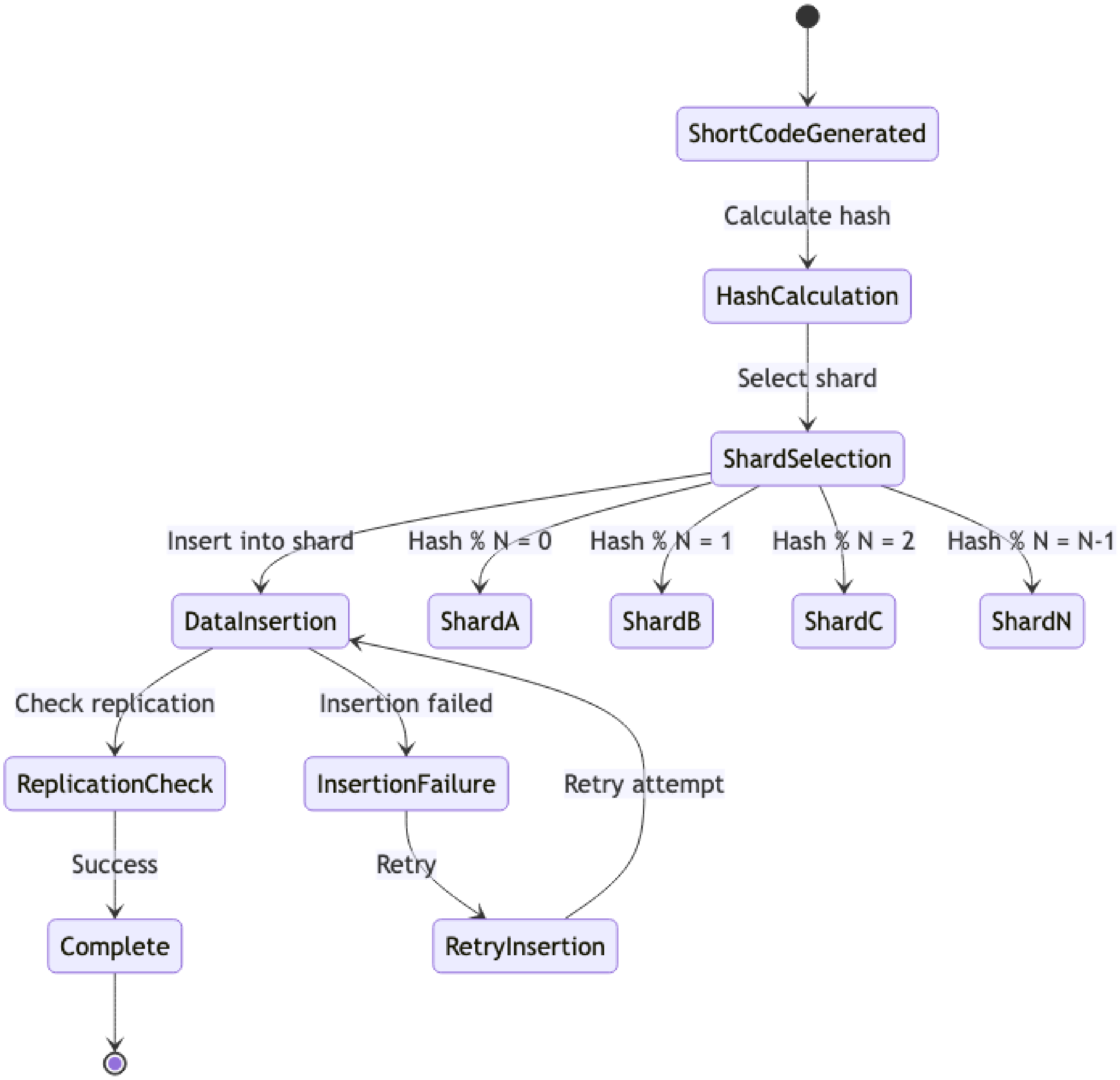

Core Algorithms

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1. Short Code Generation Algorithm

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Purpose: Generate unique, collision-resistant short codes for URLs.

Base62 Encoding Algorithm:

```
Base62Characters = "0123456789ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz"

function generateBase62Code(counter):
  if counter === 0:
    return "0"

  result = ""
  base = 62

  while counter > 0:
    remainder = counter % base
    result = Base62Characters[remainder] + result
    counter = Math.floor(counter / base)

  return result

function generateShortCode(method, input):
  switch method:
    case 'counter':
      return generateCounterBasedCode()
    case 'hash':
      return generateHashBasedCode(input)
    case 'random':
      return generateRandomCode()
    case 'timestamp':
      return generateTimestampBasedCode()

  return generateRandomCode() // fallback
```

Counter-based Generation:

```
function generateCounterBasedCode():
  // Get next counter value from distributed counter
  counter = getNextCounterValue()

  // Convert to base62
  shortCode = generateBase62Code(counter)
  // Ensure minimum length
  while shortCode.length < MIN_CODE_LENGTH:
    shortCode = "0" + shortCode

  return shortCode

function getNextCounterValue():
  // Use distributed counter with multiple ranges
  serverId = getServerId()
  rangeStart = serverId * RANGE_SIZE

  // Atomic increment within range
  localCounter = atomicIncrement(serverId)
  globalCounter = rangeStart + localCounter

  // Handle range exhaustion
  if localCounter >= RANGE_SIZE:
    requestNewRange(serverId)

  return globalCounter
```

Hash-based Generation with Collision Handling:

```
function generateHashBasedCode(url, attempt = 0):
  // Create unique input for each attempt
  input = url + attempt.toString()

  // Generate MD5 hash
  hash = md5(input)

  // Convert first 6 characters to base62
  hexSubstring = hash.substring(0, 8) // 8 hex chars = 32 bits
  decimal = parseInt(hexSubstring, 16)
  shortCode = generateBase62Code(decimal)

  // Ensure fixed length
  while shortCode.length < 6:
    shortCode = "0" + shortCode

  // Check for collision
  if checkCollision(shortCode):
    if attempt < MAX_COLLISION_ATTEMPTS:
      return generateHashBasedCode(url, attempt + 1)
    else:
      // Fallback to random generation
      return generateRandomCode()
  return shortCode
```

2. URL Validation and Normalization Algorithm

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Purpose: Ensure URLs are valid and consistently formatted before processing.

URL Validation Rules:

```
ValidationRules = {
  maxLength: 2048,
  allowedSchemes: ['http', 'https', 'ftp'],
  blockedDomains: ['malware.com', 'spam.site'],
  allowedTLD: true,
  requireValidDomain: true
}

function validateURL(url):
  validationResult = {
    isValid: false,
    errors: [],
    normalizedUrl: null
  }

  // Length check
  if url.length > ValidationRules.maxLength:
    validationResult.errors.push('URL too long')
    return validationResult

  // Parse URL
  try:
    parsedUrl = new URL(url)
  catch error:
    validationResult.errors.push('Invalid URL format')
    return validationResult

  // Scheme validation
  if not ValidationRules.allowedSchemes.includes(parsedUrl.protocol.slice(0, -1)):
    validationResult.errors.push('Invalid URL scheme')
    return validationResult

  // Domain validation
  if not isValidDomain(parsedUrl.hostname):
    validationResult.errors.push('Invalid domain')
    return validationResult

  // Blocklist check
  if ValidationRules.blockedDomains.includes(parsedUrl.hostname):
    validationResult.errors.push('Domain blocked')
    return validationResult

  // Malware/phishing check
  if await checkMalwareDatabase(parsedUrl.hostname):
    validationResult.errors.push('Malicious URL detected')
    return validationResult

  validationResult.isValid = true
  validationResult.normalizedUrl = normalizeURL(parsedUrl)
  return validationResult
```

URL Normalization Algorithm:

```
function normalizeURL(parsedUrl):
  normalized = {
    protocol: parsedUrl.protocol.toLowerCase(),
    hostname: parsedUrl.hostname.toLowerCase(),
    pathname: parsedUrl.pathname,
    search: parsedUrl.search,
    hash: parsedUrl.hash
  }

  // Remove default ports
  if (normalized.protocol === 'http:' and parsedUrl.port === '80') or
     (normalized.protocol === 'https:' and parsedUrl.port === '443'):
    // Don't include port
  else if parsedUrl.port:
    normalized.port = parsedUrl.port

  // Normalize pathname
  normalized.pathname = removeTrailingSlash(normalized.pathname)
  normalized.pathname = resolveRelativePaths(normalized.pathname)

  // Sort query parameters for consistency
  if normalized.search:
    queryParams = new URLSearchParams(normalized.search)
    queryParams.sort()
    normalized.search = '?' + queryParams.toString()

  // Remove fragment for certain cases
  if shouldRemoveFragment(normalized):
    normalized.hash = ''

  return constructURL(normalized)
```

3. Caching Strategy Algorithm

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Purpose: Optimize performance through intelligent multi-layer caching.

Cache Hierarchy Management:

```
CacheConfig = {
  localCache: {
    maxSize: 10000,
    ttl: 300, // 5 minutes
    algorithm: 'LRU'
  },
  redisCache: {
    ttl: 3600, // 1 hour
    keyPrefix: 'url:',
    compressionEnabled: true
  },
  cdnCache: {
    ttl: 86400, // 24 hours
    edgeLocations: true,
    compressionEnabled: true
  }
}

function getCachedURL(shortCode):
  // Level 1: Local cache
  result = localCache.get(shortCode)
  if result:
    updateCacheStats('local_hit')
    return result

  // Level 2: Redis cache
  result = redisCache.get(CacheConfig.redisCache.keyPrefix + shortCode)
  if result:
    // Promote to local cache
    localCache.set(shortCode, result, CacheConfig.localCache.ttl)
    updateCacheStats('redis_hit')
    return result
  // Level 3: Database lookup
  result = database.lookup(shortCode)
  if result:
    // Populate all cache levels
    setCachedURL(shortCode, result)
    updateCacheStats('db_hit')
    return result

  updateCacheStats('miss')
  return null
```

Cache Invalidation Strategy:

```
function invalidateCache(shortCode, reason):
  invalidationTasks = []

  // Remove from local cache
  invalidationTasks.push(localCache.delete(shortCode))

  // Remove from Redis cache
  invalidationTasks.push(redisCache.delete(CacheConfig.redisCache.keyPrefix + shortCode)

  // For CDN invalidation, depends on reason
  if reason === 'url_updated' or reason === 'url_deleted':
    invalidationTasks.push(cdnInvalidate(shortCode))

  // Log invalidation for monitoring
  logCacheInvalidation(shortCode, reason, Date.now())

  return Promise.all(invalidationTasks)

function determineInvalidationScope(operation, shortCode):
  switch operation:
    case 'url_delete':
      return ['local', 'redis', 'cdn']
    case 'url_update':
      return ['local', 'redis', 'cdn']
    case 'analytics_update':
      return [] // Analytics don't affect URL resolution
    case 'metadata_update':
      return ['local', 'redis'] // CDN can keep serving redirects
    default:
      return ['local', 'redis']
```

4. Analytics and Tracking Algorithm

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Purpose: Collect and process URL usage analytics efficiently.

Real-time Analytics Collection:

```
AnalyticsEvent = {
  shortCode: string,
  timestamp: number,
  ipAddress: string,
  userAgent: string,
  referrer: string,
  geolocation: {
    country: string,
    region: string,
    city: string
  },
  deviceInfo: {
    type: string, // mobile, desktop, tablet
    os: string,
    browser: string
  }
}

function trackURLAccess(shortCode, request):
  event = {
    shortCode: shortCode,
    timestamp: Date.now(),
    ipAddress: extractClientIP(request),
    userAgent: request.headers['user-agent'],
    referrer: request.headers['referer'] || 'direct'
  }

  // Async processing to not block redirect
  Promise.resolve().then(() => {
    // Enrich with geolocation
    event.geolocation = getGeolocation(event.ipAddress)

    // Parse user agent
    event.deviceInfo = parseUserAgent(event.userAgent)

    // Store in analytics database
    storeAnalyticsEvent(event)
    // Update real-time counters
    updateRealTimeCounters(shortCode, event)

    // Stream to analytics pipeline
    streamToAnalyticsPipeline(event)
  })
```

Analytics Aggregation Algorithm:

```
function aggregateAnalytics(shortCode, timeRange):
  rawEvents = getAnalyticsEvents(shortCode, timeRange)

  aggregation = {
    totalClicks: rawEvents.length,
    uniqueClicks: 0,
    topReferrers: new Map(),
    topCountries: new Map(),
    deviceTypes: new Map(),
    browsers: new Map(),
    hourlyDistribution: new Array(24).fill(0),
    dailyTrend: []
  }

  uniqueIPs = new Set()

  for event in rawEvents:
    // Count unique IPs (proxy for unique users)
    uniqueIPs.add(event.ipAddress)

    // Aggregate referrers
    incrementCounter(aggregation.topReferrers, event.referrer)

    // Aggregate geography
    incrementCounter(aggregation.topCountries, event.geolocation.country)

    // Aggregate device types
    incrementCounter(aggregation.deviceTypes, event.deviceInfo.type)

    // Aggregate browsers
    incrementCounter(aggregation.browsers, event.deviceInfo.browser)

    // Hourly distribution
    hour = new Date(event.timestamp).getHours()
    aggregation.hourlyDistribution[hour]++
    // Daily trend
    updateDailyTrend(aggregation.dailyTrend, event.timestamp)

  aggregation.uniqueClicks = uniqueIPs.size

  // Sort and limit top lists
  aggregation.topReferrers = sortAndLimit(aggregation.topReferrers, 10)
  aggregation.topCountries = sortAndLimit(aggregation.topCountries, 10)

  return aggregation
```

5. Rate Limiting Algorithm

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Purpose: Prevent abuse and ensure fair usage of the service.

Token Bucket Rate Limiter:

```
TokenBucket = {
  capacity: number,
  tokens: number,
  refillRate: number, // tokens per second
  lastRefill: number
}

function createRateLimiter(userId, endpoint):
  limits = getRateLimits(userId, endpoint)

  return {
    bucket: {
      capacity: limits.maxRequests,
      tokens: limits.maxRequests,
      refillRate: limits.refillRate,
      lastRefill: Date.now()
    },
    windowStart: Date.now(),
    requestCount: 0
  }

function checkRateLimit(userId, endpoint, requestCount = 1):
  rateLimiter = getRateLimiter(userId, endpoint)

  // Refill tokens based on time elapsed
  refillTokens(rateLimiter.bucket)
  // Check if enough tokens available
  if rateLimiter.bucket.tokens >= requestCount:
    rateLimiter.bucket.tokens -= requestCount
    return {
      allowed: true,
      remainingTokens: rateLimiter.bucket.tokens,
      resetTime: calculateResetTime(rateLimiter.bucket)
    }
  else:
    return {
      allowed: false,
      remainingTokens: rateLimiter.bucket.tokens,
      resetTime: calculateResetTime(rateLimiter.bucket),
      retryAfter: calculateRetryAfter(rateLimiter.bucket, requestCount)
    }
```

Adaptive Rate Limiting:

```
function getAdaptiveRateLimit(userId, endpoint, context):
  baseLimit = getBaseLimits(userId, endpoint)

  // Adjust based on user tier
  userTier = getUserTier(userId)
  tierMultiplier = getTierMultiplier(userTier)

  // Adjust based on system load
  systemLoad = getCurrentSystemLoad()
  loadMultiplier = calculateLoadMultiplier(systemLoad)

  // Adjust based on user behavior
  userReputation = getUserReputation(userId)
  reputationMultiplier = calculateReputationMultiplier(userReputation)

  // Adjust based on endpoint sensitivity
  endpointSensitivity = getEndpointSensitivity(endpoint)
  sensitivityMultiplier = calculateSensitivityMultiplier(endpointSensitivity)

  finalLimit = Math.floor(
    baseLimit *
    tierMultiplier *
    loadMultiplier *
    reputationMultiplier *
    sensitivityMultiplier
  )
  return Math.max(finalLimit, MIN_RATE_LIMIT)
```

Component Architecture

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Microservices Architecture

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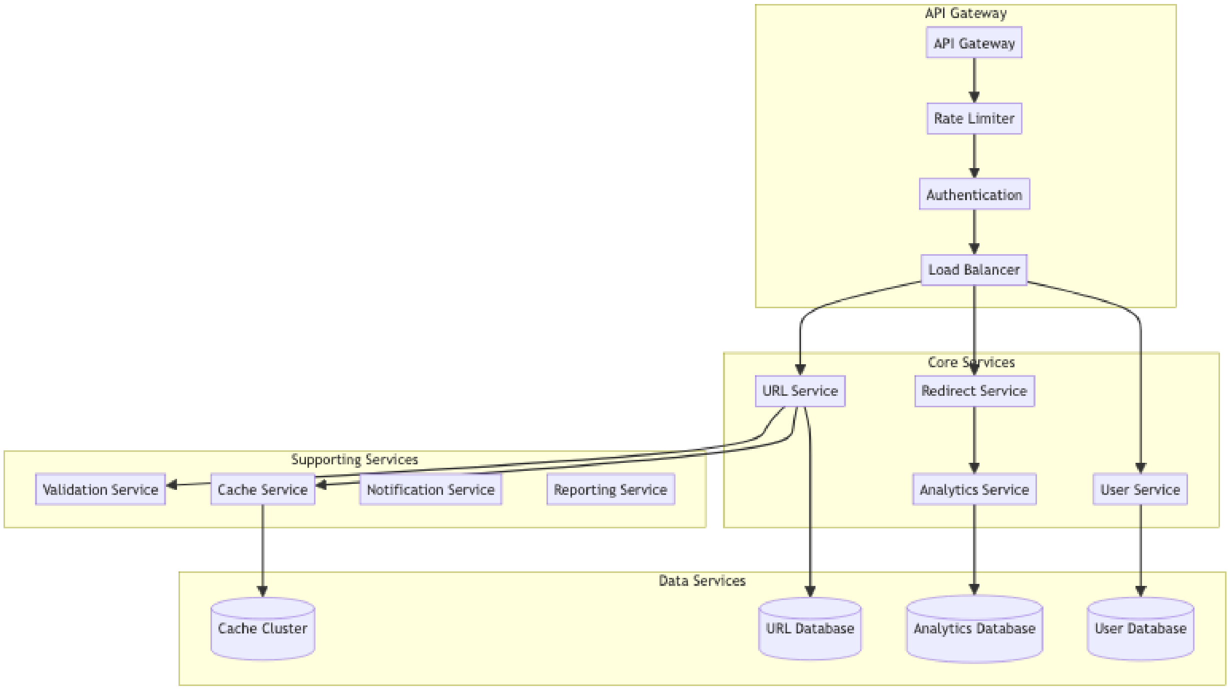

Database Schema Design

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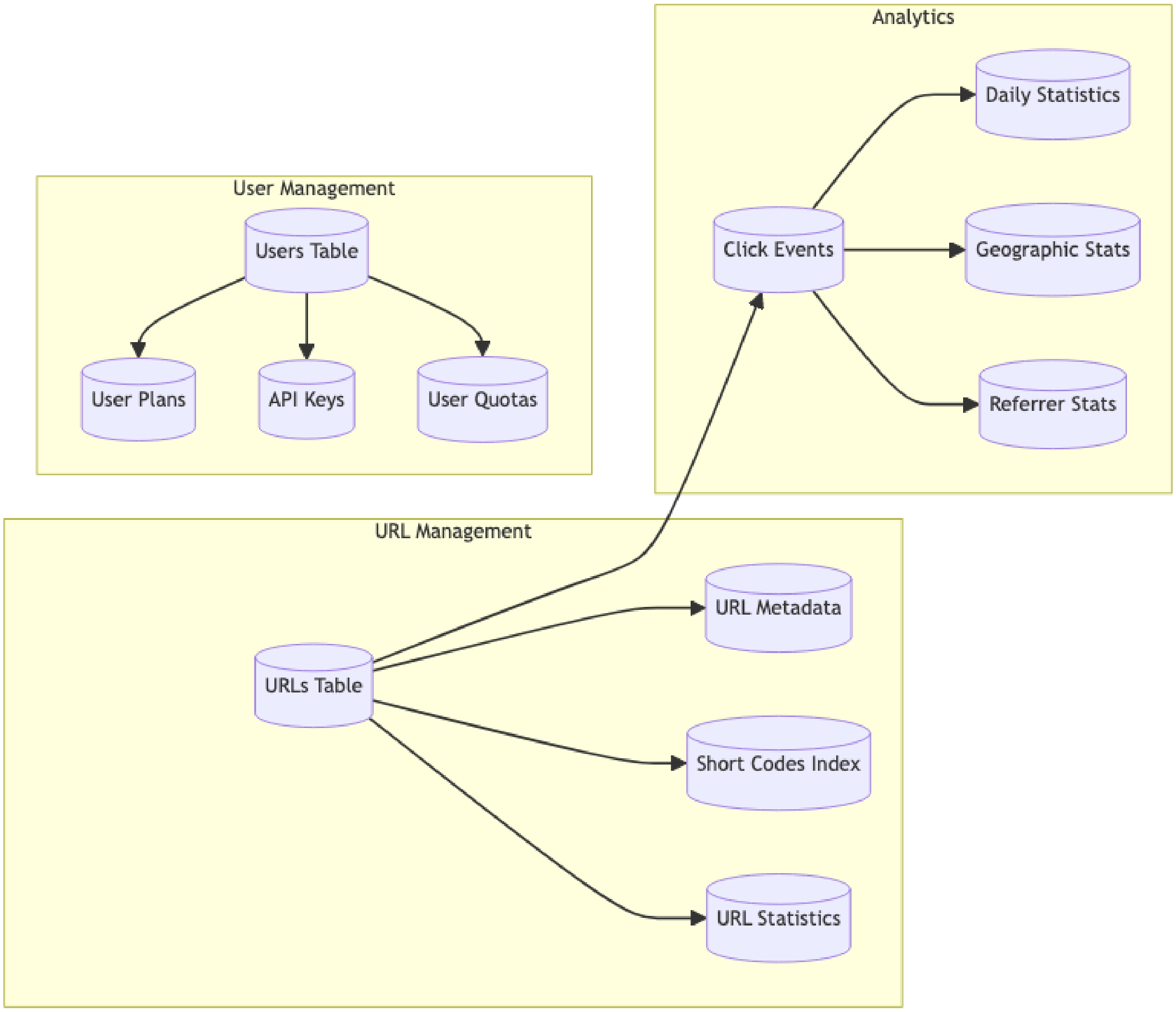

Advanced Features

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Custom Short URLs and Branding

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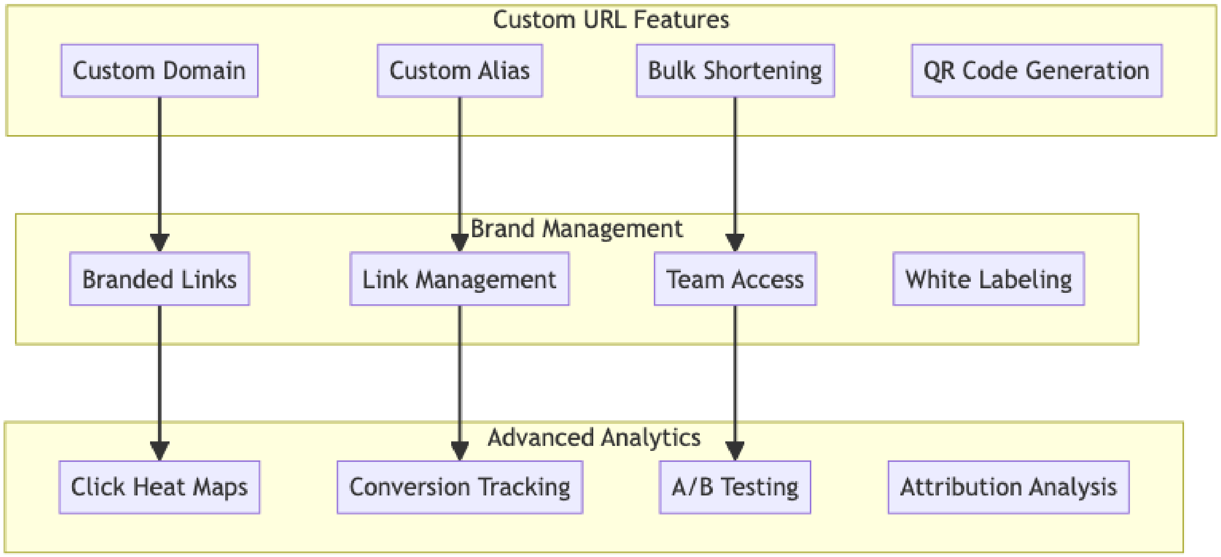

Security and Fraud Detection

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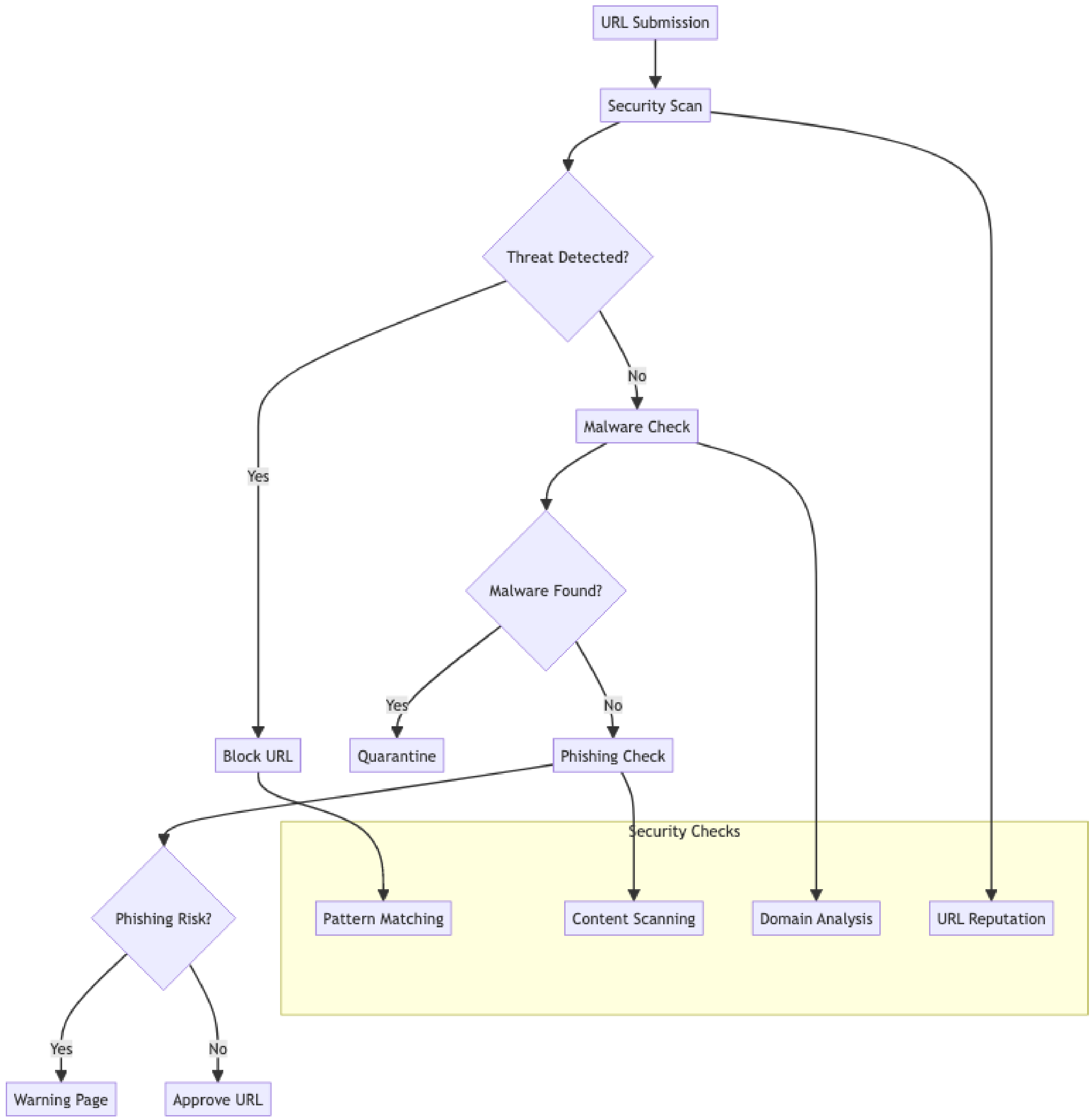

Performance Optimizations

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Horizontal Scaling Strategy

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Database Sharding:

```
ShardingStrategy = {
  method: 'hash_based',
  shardKey: 'short_code',
  shardCount: 64,
  replicationFactor: 3
}
```

Read Replica Optimization: - Use read replicas for analytics queries - Implement eventual consistency for non-critical reads - Route read traffic based on geographic proximity - Cache frequently accessed data

CDN and Edge Computing

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Edge Caching Strategy: - Cache popular short URLs at edge locations - Implement cache warming for trending links - Use intelligent cache invalidation - Optimize cache hit ratios through predictive caching

Connection Pooling and Resource Management

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Database Connection Optimization: - Implement connection pooling with proper sizing - Use prepared statements for common queries - Optimize query patterns for read/write workloads - Monitor and tune database performance metrics

Security Considerations

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URL Security Framework

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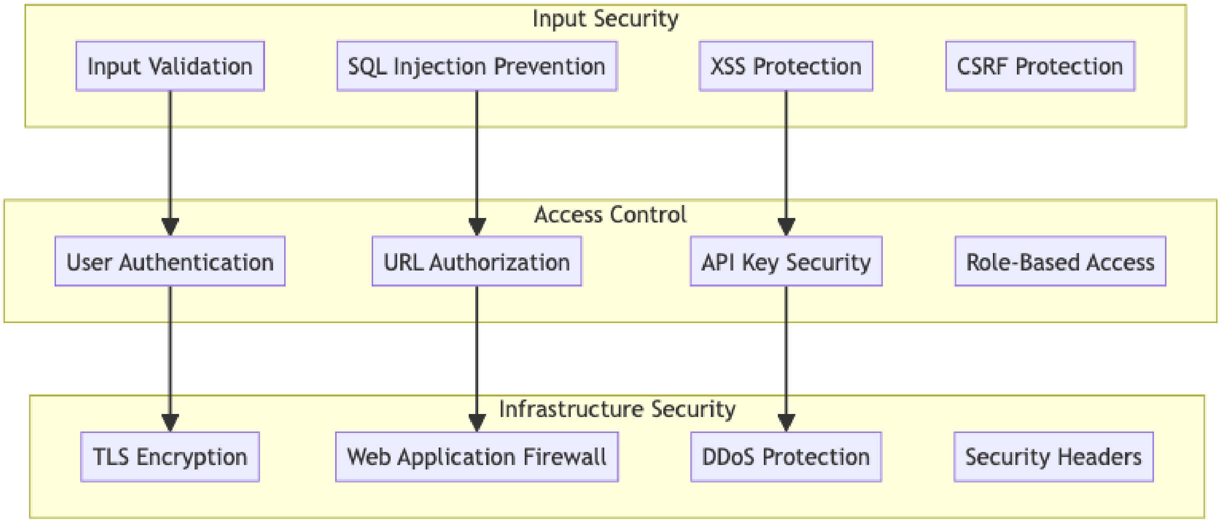

Data Protection and Privacy

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Privacy Framework: - Implement data anonymization for analytics - Provide user data export functionality - Support GDPR right to be forgotten - Encrypt sensitive data at rest and in transit - Regular security audits and penetration testing

Testing Strategy

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Performance Testing

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Load Testing Scenarios: - URL shortening API throughput testing - Redirect service performance under load - Database query performance optimization - Cache performance and hit ratio validation

Stress Testing: - Peak traffic simulation - Database failover testing - Cache invalidation impact - Rate limiting effectiveness

Security Testing

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Security Test Cases: - Malicious URL detection accuracy - SQL injection prevention - Rate limiting bypass attempts - Authentication and authorization testing

Trade-offs and Considerations

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Performance vs Accuracy

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- **Caching duration**: Faster redirects vs analytics accuracy
- **Database consistency**: Performance vs data consistency
- **Code generation**: Speed vs collision probability
- **Rate limiting**: User experience vs abuse prevention

Scalability vs Cost

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- **Database scaling**: Read replicas vs infrastructure cost
- **CDN coverage**: Global performance vs CDN expenses
- **Cache layers**: Memory usage vs response times
- **Analytics granularity**: Data insights vs storage costs

Security vs Usability

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- **URL validation**: Security vs user convenience
- **Rate limiting**: Abuse prevention vs legitimate usage
- **Analytics tracking**: Insights vs user privacy
- **Custom domains**: Branding vs security complexity

This URL shortener service provides a comprehensive foundation for high-scale link shortening with features like intelligent caching, advanced analytics, and robust security measures while maintaining excellent performance and reliability standards.