Real-time Chat Messaging Backend

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Requirements Gathering

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Functional Requirements

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Core Messaging Features: - Send and receive text messages in real-time - Support group chats (up to 1000 members per group) - Send multimedia files (images, videos, documents) up to 100MB - Message delivery status (sent, delivered, read) - Message history and persistence - Online/offline presence indicators - Typing indicators - Message reactions and emoji responses - Reply to specific messages (threading) - Forward messages to other chats - Search messages across conversations - Delete messages (for self and for everyone) - Edit sent messages within 5 minutes

User Management: - User registration and authentication - User profiles with photos and status - Block/unblock users - Report inappropriate content - Contact management and friend requests

Advanced Features: - End-to-end encryption for privacy - Message scheduling - Disappearing messages (auto-delete after time) - Voice and video calling - Screen sharing - File sharing with version control - Message translation - Chat backups and sync across devices

Non-Functional Requirements

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Performance: - Message delivery latency < 100ms for same region - Support 50 million daily active users - Handle 1 billion messages per day - 99.9% uptime SLA - Auto-scaling to handle traffic spikes

Scalability: - Horizontal scaling of all services - Handle 10x traffic growth - Global distribution across multiple regions - Support for 100,000 concurrent connections per server

Security: - End-to-end encryption for all messages - Secure file transfer with virus scanning - Authentication and authorization - Rate limiting to prevent spam - DDoS protection - GDPR and privacy compliance

Reliability: - Message durability (no message loss) - Automatic failover and disaster recovery - Data replication across multiple data centers - Circuit breaker patterns for fault tolerance

Traffic Estimation & Capacity Planning

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User Base Analysis

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- **Total Users:** 100 million registered users
- **Daily Active Users (DAU):** 50 million users
- **Peak Concurrent Users:** 10 million users
- **Messages per User per Day:** 50 messages average
- **Peak Traffic Ratio:** 3x average during peak hours

Traffic Calculations

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Message Volume:

```
Daily Messages = 50M DAU × 50 messages = 2.5B messages/day
Peak Messages/sec = (2.5B × 3) / (24 × 3600) = 2,600 messages/sec
Average Messages/sec = 2.5B / (24 × 3600) = 29,000 messages/sec

Group Messages (30% of traffic):
- Group message fanout = Average 10 recipients
- Effective peak load = 2,600 × 1.3 × 10 = 33,800 deliveries/sec
```

Connection Requirements:

```
WebSocket Connections:
- Peak concurrent connections = 10M users
- Connection memory per user = 8KB
- Total memory for connections = 10M × 8KB = 80GB
- Servers needed (assuming 100K connections/server) = 100 servers
```

Storage Requirements:

```
Message Storage:
- Average message size = 200 bytes (text + metadata)
- Multimedia messages = 5% of total, average 2MB each
- Daily storage = (2.5B × 200B) + (2.5B × 0.05 × 2MB) = 750GB/day
- Annual storage = 750GB × 365 = 274TB/year
- With 3x replication = 822TB/year

File Storage:
- Daily file uploads = 50M users × 2 files × 5MB = 500TB/day
- With CDN and compression (70% reduction) = 150TB/day
```

Bandwidth Requirements:

```
Message Traffic:
- Peak message bandwidth = 33,800 msg/sec × 200B = 6.76MB/s
- With protocol overhead (2x) = 13.5MB/s

File Transfer:
- Peak file transfer = 10,000 files/sec × 5MB = 50GB/s
- With CDN distribution = 5GB/s core bandwidth
```

Infrastructure Sizing:

```
Application Servers:
- Message processing: 20 servers (with 2x redundancy)
- WebSocket handling: 100 servers
- File processing: 30 servers

Database Requirements:
- Message DB: 50 shards, 32GB RAM each
- User DB: 10 shards, 64GB RAM each
- File metadata DB: 5 shards, 16GB RAM each

Cache Requirements:
- Redis clusters: 200GB total memory
- Recent messages cache: 50GB
- User presence cache: 30GB
- File metadata cache: 20GB
```

Database Schema Design

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Message Database Schema

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```
-- Messages table (sharded by chat_id)
CREATE TABLE messages (
    message_id BIGINT PRIMARY KEY,
    chat_id BIGINT NOT NULL,
    sender_id BIGINT NOT NULL,
    message_type ENUM('text', 'image', 'video', 'file', 'audio') NOT NULL,
    content TEXT,
    file_url VARCHAR(512),
    file_size BIGINT,
    reply_to_message_id BIGINT,
    is_edited BOOLEAN DEFAULT FALSE,
    is_deleted BOOLEAN DEFAULT FALSE,
    created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
    updated_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP ON UPDATE CURRENT_TIMESTAMP,
    delivery_status ENUM('sent', 'delivered', 'read') DEFAULT 'sent',

    INDEX idx_chat_created (chat_id, created_at),
    INDEX idx_sender_created (sender_id, created_at),
    FOREIGN KEY (reply_to_message_id) REFERENCES messages(message_id)
);

-- Chats table
CREATE TABLE chats (
    chat_id BIGINT PRIMARY KEY AUTO_INCREMENT,
    chat_type ENUM('direct', 'group') NOT NULL,
    chat_name VARCHAR(255),
    chat_description TEXT,
    created_by BIGINT NOT NULL,
    created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
    updated_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP ON UPDATE CURRENT_TIMESTAMP,
    is_active BOOLEAN DEFAULT TRUE,
    max_members INT DEFAULT 1000,

    INDEX idx_created_by (created_by),
    INDEX idx_type_created (chat_type, created_at)
);

-- Chat participants table
CREATE TABLE chat_participants (
    chat_id BIGINT NOT NULL,
    user_id BIGINT NOT NULL,
    role ENUM('admin', 'moderator', 'member') DEFAULT 'member',
    joined_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
    last_read_message_id BIGINT,
    is_muted BOOLEAN DEFAULT FALSE,

    PRIMARY KEY (chat_id, user_id),
    INDEX idx_user_joined (user_id, joined_at),
    FOREIGN KEY (chat_id) REFERENCES chats(chat_id),
    FOREIGN KEY (last_read_message_id) REFERENCES messages(message_id)
);

-- Message delivery tracking
CREATE TABLE message_delivery (
    message_id BIGINT NOT NULL,
    user_id BIGINT NOT NULL,
    delivery_status ENUM('sent', 'delivered', 'read') NOT NULL,
    delivered_at TIMESTAMP NULL,
    read_at TIMESTAMP NULL,

    PRIMARY KEY (message_id, user_id),
    INDEX idx_user_status (user_id, delivery_status),
    FOREIGN KEY (message_id) REFERENCES messages(message_id)
);

-- Message reactions
CREATE TABLE message_reactions (
    reaction_id BIGINT PRIMARY KEY AUTO_INCREMENT,
    message_id BIGINT NOT NULL,
    user_id BIGINT NOT NULL,
    reaction_type VARCHAR(50) NOT NULL, -- emoji unicode
    created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,

    UNIQUE KEY unique_user_message_reaction (message_id, user_id, reaction_type),
    INDEX idx_message_reactions (message_id),
    FOREIGN KEY (message_id) REFERENCES messages(message_id)
);
```

User Database Schema

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```
-- Users table
CREATE TABLE users (
```

```sql
    user_id BIGINT PRIMARY KEY AUTO_INCREMENT,
    username VARCHAR(50) UNIQUE NOT NULL,
    email VARCHAR(255) UNIQUE NOT NULL,
    phone_number VARCHAR(20) UNIQUE,
    password_hash VARCHAR(255) NOT NULL,
    first_name VARCHAR(100),
    last_name VARCHAR(100),
    profile_picture_url VARCHAR(512),
    status_message VARCHAR(255),
    last_seen TIMESTAMP,
    is_online BOOLEAN DEFAULT FALSE,
    privacy_settings JSON,
    created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
    updated_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP ON UPDATE CURRENT_TIMESTAMP,
    is_active BOOLEAN DEFAULT TRUE,

    INDEX idx_username (username),
    INDEX idx_email (email),
    INDEX idx_last_seen (last_seen)
);

-- User sessions for presence management
CREATE TABLE user_sessions (
    session_id VARCHAR(128) PRIMARY KEY,
    user_id BIGINT NOT NULL,
    device_type ENUM('web', 'mobile', 'desktop') NOT NULL,
    device_id VARCHAR(255),
    ip_address VARCHAR(45),
    user_agent TEXT,
    created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
    last_activity TIMESTAMP DEFAULT CURRENT_TIMESTAMP ON UPDATE CURRENT_TIMESTAMP,
    is_active BOOLEAN DEFAULT TRUE,

    INDEX idx_user_active (user_id, is_active),
    INDEX idx_last_activity (last_activity),
    FOREIGN KEY (user_id) REFERENCES users(user_id)
);

-- User contacts/friends
CREATE TABLE user_contacts (
    user_id BIGINT NOT NULL,
    contact_user_id BIGINT NOT NULL,
    contact_name VARCHAR(255), -- custom name for contact
    is_blocked BOOLEAN DEFAULT FALSE,
    added_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
    PRIMARY KEY (user_id, contact_user_id),
    INDEX idx_contact_user (contact_user_id),
    FOREIGN KEY (user_id) REFERENCES users(user_id),
    FOREIGN KEY (contact_user_id) REFERENCES users(user_id)
);
```

File Storage Schema

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```
-- File metadata table
CREATE TABLE file_metadata (
    file_id VARCHAR(128) PRIMARY KEY, -- UUID
    original_filename VARCHAR(255) NOT NULL,
    file_type VARCHAR(50) NOT NULL,
    file_size BIGINT NOT NULL,
    mime_type VARCHAR(100),
    storage_path VARCHAR(512) NOT NULL,
    thumbnail_path VARCHAR(512),
    uploaded_by BIGINT NOT NULL,
    upload_ip VARCHAR(45),
    is_scanned BOOLEAN DEFAULT FALSE, -- virus scan status
    scan_result ENUM('clean', 'infected', 'pending') DEFAULT 'pending',
    created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
    expires_at TIMESTAMP NULL, -- for temporary files
    download_count INT DEFAULT 0,

    INDEX idx_uploaded_by (uploaded_by),
    INDEX idx_file_type (file_type),
    INDEX idx_created_at (created_at),
    FOREIGN KEY (uploaded_by) REFERENCES users(user_id)
);
```

Sample API Endpoints

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Authentication APIs

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```
POST /api/v1/auth/register
Content-Type: application/json

{
    "username": "john_doe",
    "email": "john@example.com",
    "password": "YOUR_PASSWORD_HERE",
    "first_name": "John",
    "last_name": "Doe"
}

Response (201 Created):
{
    "success": true,
    "data": {
        "user_id": 12345,
        "username": "john_doe",
        "email": "john@example.com",
        "access_token": "eyJhbGciOiJIUzI1NiIsInR5cCI6IkpXVCJ9...",
        "refresh_token": "eyJhbGciOiJIUzI1NiIsInR5cCI6IkpXVCJ9...",
        "expires_in": 3600
    }
}
```

```
POST /api/v1/auth/login
Content-Type: application/json

{
    "username": "...",
    "pass": "..."
}

Response (200 OK):
{
    "success": true,
    "data": {
        "user_id": 12345,
        "username": "john_doe",
        "access_token": "eyJhbGciOiJIUzI1NiIsInR5cCI6IkpXVCJ9...",
        "refresh_token": "eyJhbGciOiJIUzI1NiIsInR5cCI6IkpXVCJ9...",
        "expires_in": 3600
    }
}
```

Messaging APIs

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```
POST /api/v1/chats
Authorization: Bearer <access_token>
Content-Type: application/json

{
    "chat_type": "group",
    "chat_name": "Project Team",
    "participants": [12346, 12347, 12348]
}

Response (201 Created):
{
    "success": true,
    "data": {
        "chat_id": 98765,
        "chat_type": "group",
        "chat_name": "Project Team",
        "created_by": 12345,
        "participants": [
            {"user_id": 12345, "role": "admin"},
            {"user_id": 12346, "role": "member"},
            {"user_id": 12347, "role": "member"},
            {"user_id": 12348, "role": "member"}
        ],
        "created_at": "2024-01-15T10:30:00Z"
    }
}
```

```
POST /api/v1/chats/{chat_id}/messages
Authorization: Bearer <access_token>
Content-Type: application/json

{
    "message_type": "text",
    "content": "Hello team! How's the project going?",
    "reply_to_message_id": null
}

Response (201 Created):
{
    "success": true,
    "data": {
        "message_id": 567890,
        "chat_id": 98765,
        "sender_id": 12345,
        "message_type": "text",
        "content": "Hello team! How's the project going?",
        "created_at": "2024-01-15T10:35:00Z",
        "delivery_status": "sent"
    }
}
```

```
GET /api/v1/chats/{chat_id}/messages?limit=50&before_id=567890
Authorization: Bearer <access_token>

Response (200 OK):
{
    "success": true,
    "data": {
        "messages": [
            {
                "message_id": 567889,
                "sender_id": 12346,
                "message_type": "text",
                "content": "Everything's on track!",
                "created_at": "2024-01-15T10:34:00Z",
                "sender": {
                    "user_id": 12346,
                    "username": "jane_smith",
                    "profile_picture_url": "https://cdn.example.com/profiles/jane.jpg"
                },
                "reactions": [
                    {"reaction_type": " ", "count": 2, "users": [12345, 12347]}
                ]
            }
        ],
        "has_more": true,
        "next_before_id": 567888
    }
}
```

File Upload APIs

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```
POST /api/v1/files/upload
Authorization: Bearer <access_token>
Content-Type: multipart/form-data

Form Data:
- file: [binary file data]
- chat_id: 98765

Response (201 Created):
{
    "success": true,
    "data": {
        "file_id": "abc123-def456-789ghi",
        "original_filename": "project_screenshot.png",
        "file_type": "image",
        "file_size": 2048576,
        "file_url": "https://cdn.example.com/files/abc123-def456-789ghi.png",
        "thumbnail_url": "https://cdn.example.com/thumbnails/abc123-def456-789ghi_thumb.
        "upload_status": "completed"
    }
}
```

WebSocket APIs

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```javascript
// WebSocket connection establishment
const ws = new WebSocket('wss://api.example.com/ws');

// Authentication after connection
ws.send(JSON.stringify({
    type: 'auth',
    token: 'eyJhbGciOiJIUzI1NiIsInR5cCI6IkpXVCJ9...'
}));

// Join chat rooms
ws.send(JSON.stringify({
    type: 'join_chat',
    chat_id: 98765
}));

// Send real-time message
ws.send(JSON.stringify({
    type: 'send_message',
    chat_id: 98765,
    message_type: 'text',
    content: 'Hello everyone!',
    temp_id: 'temp_123' // for client-side deduplication
}));

// Receive message events
ws.onmessage = (event) => {
    const data = JSON.parse(event.data);
    switch(data.type) {
        case 'new_message':
            // Handle new message
            break;
        case 'message_delivered':
            // Update delivery status
            break;
        case 'user_typing':
            // Show typing indicator
            break;
        case 'presence_update':
            // Update user online status
            break;
    }
};
```

High-Level Design (HLD)

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System Architecture Overview

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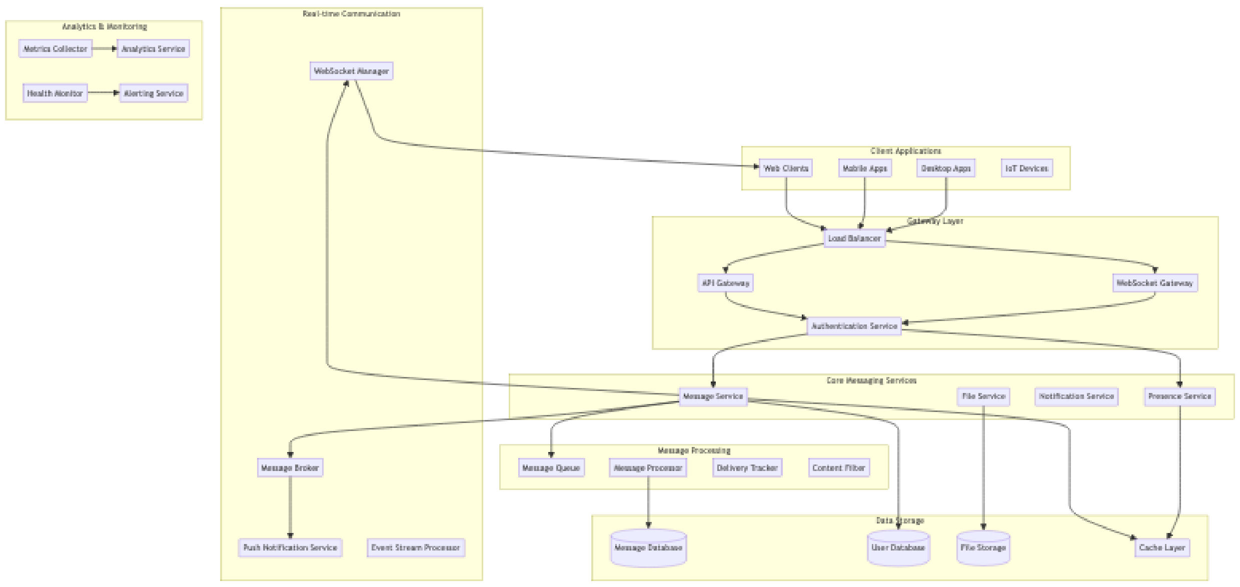

Message Flow Architecture

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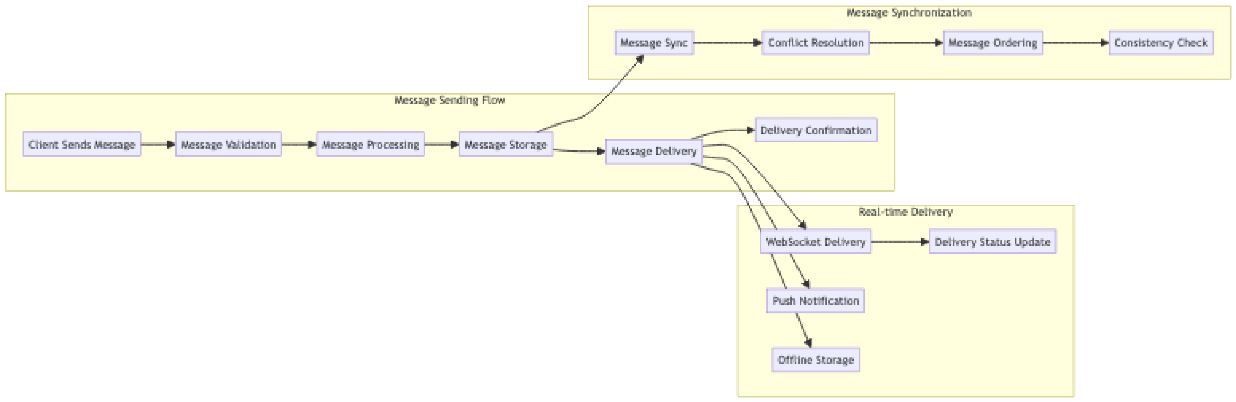

Low-Level Design (LLD)

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WebSocket Connection Management

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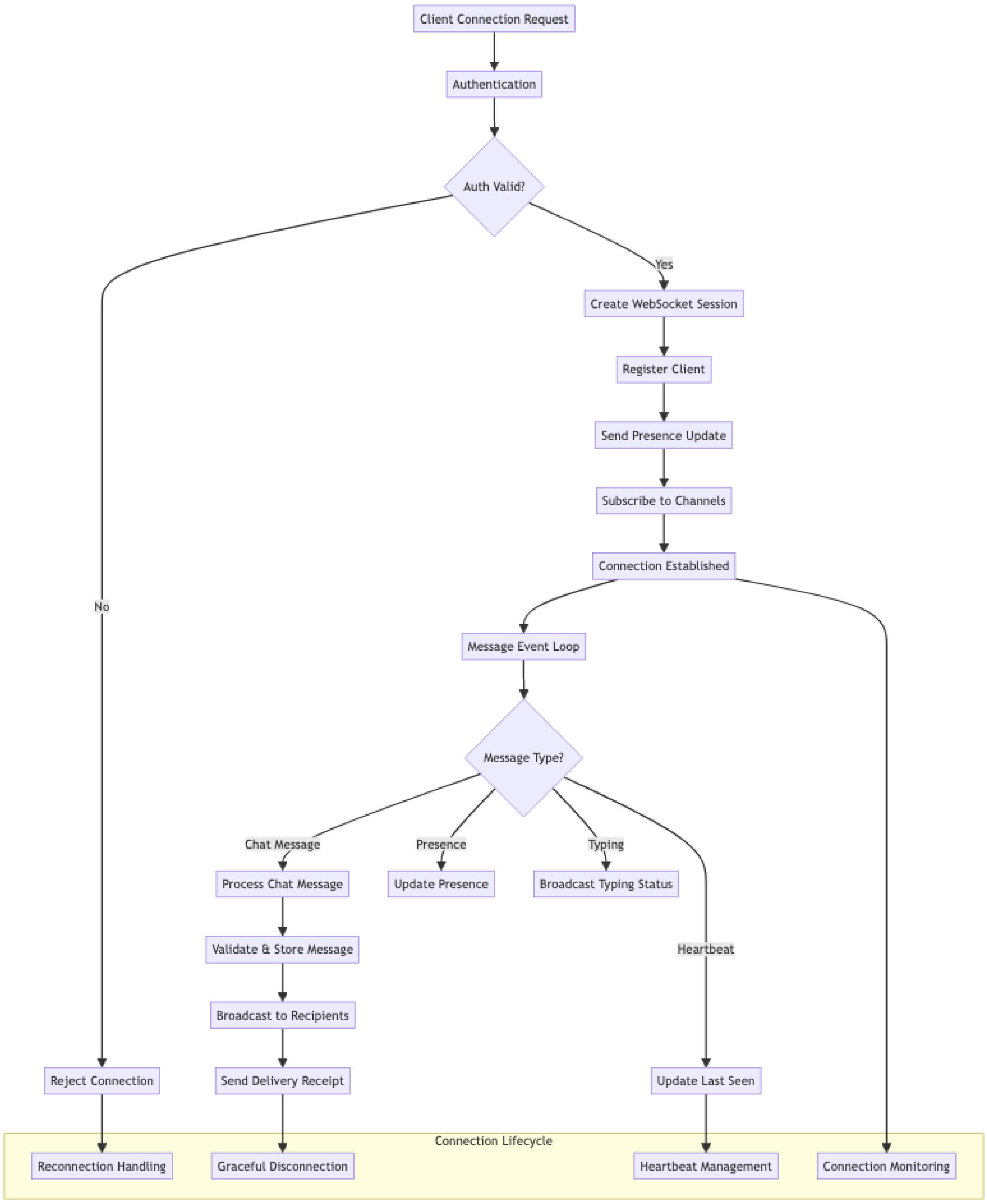

Message Ordering and Consistency

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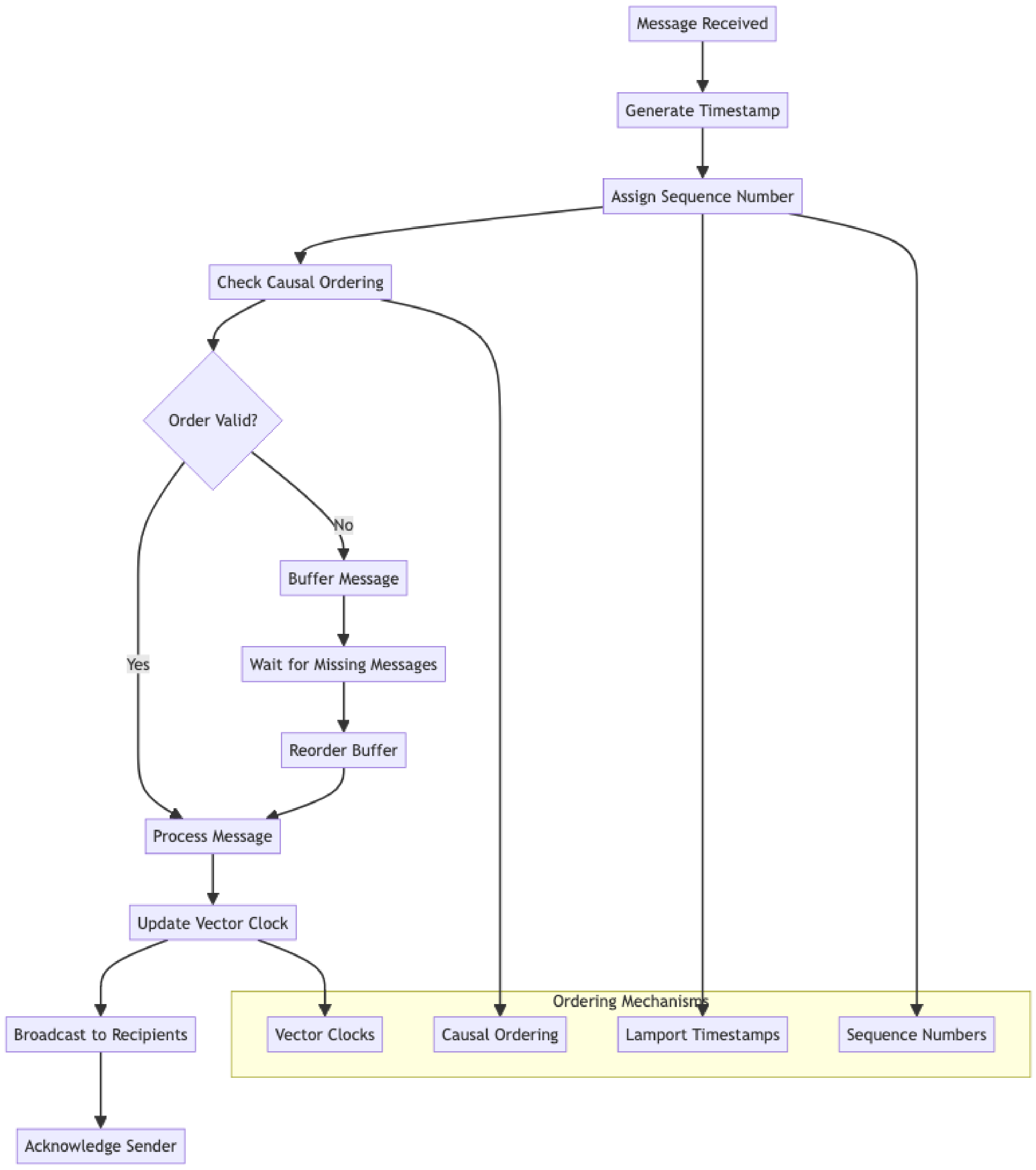

Presence Management System

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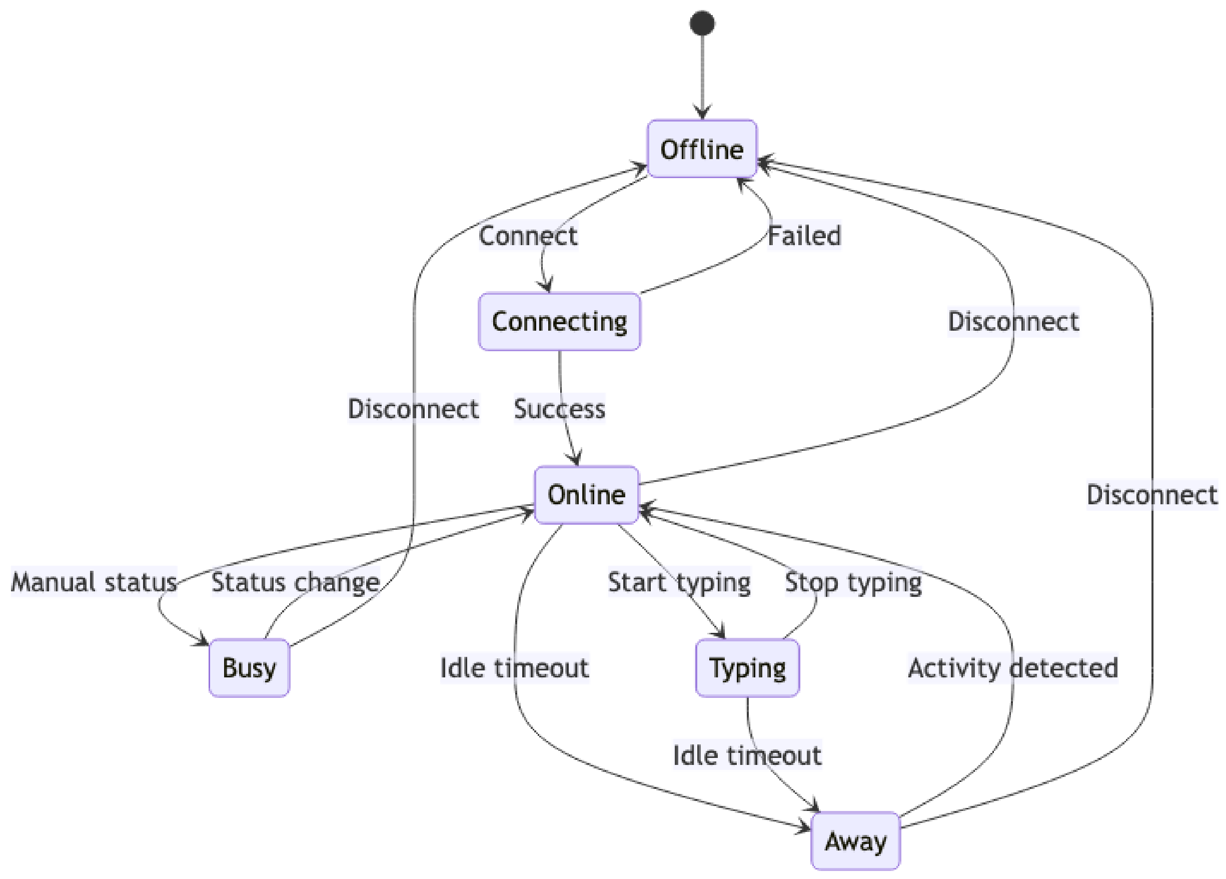

Core Algorithms

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1. Message Ordering and Consistency Algorithm

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Purpose: Ensure messages are delivered in the correct order across distributed clients while maintaining causal consistency.

Vector Clock Implementation:

```
MessageOrderingConfig = {
  orderingStrategy: 'causal_ordering',      // 'fifo', 'causal_ordering', 'total_ordering
  vectorClockSize: 100,                     // Max participants in vector clock
  bufferSize: 1000,                         // Message buffer size
  maxWaitTime: 5000,                        // Max wait for missing messages
  consistencyLevel: 'causal',             // 'eventual', 'causal', 'strong'
  reorderingEnabled: true,
  duplicateDetection: true
}

class MessageOrderingManager:
  constructor(config):
    this.config = config
    this.vectorClock = new Map()          // participantId -> clock value
    this.messageBuffer = new Map()        // conversationId -> buffered messages
    this.processedMessages = new Set()    // For duplicate detection
    this.sequenceNumbers = new Map()      // conversationId -> sequence counter

  function processMessage(message, senderId, conversationId):
    # Generate message ordering metadata
    orderingInfo = this.generateOrderingInfo(message, senderId, conversationId)

    # Check for duplicates
    if this.isDuplicate(message, orderingInfo):
      return { processed: false, reason: 'duplicate' }

    # Check if message can be processed immediately
    if this.canProcessImmediately(message, orderingInfo, conversationId):
      return this.processImmediately(message, orderingInfo, conversationId)
    else:
      # Buffer message and wait for missing predecessors
      return this.bufferMessage(message, orderingInfo, conversationId)

  function generateOrderingInfo(message, senderId, conversationId):
    currentTime = Date.now()

    # Update sender's vector clock
    if not this.vectorClock.has(senderId):
      this.vectorClock.set(senderId, 0)

    senderClock = this.vectorClock.get(senderId) + 1
    this.vectorClock.set(senderId, senderClock)

    # Generate sequence number for conversation
    if not this.sequenceNumbers.has(conversationId):
      this.sequenceNumbers.set(conversationId, 0)

    sequenceNumber = this.sequenceNumbers.get(conversationId) + 1
    this.sequenceNumbers.set(conversationId, sequenceNumber)
    # Create ordering metadata
    orderingInfo = {
      messageId: message.id,
      senderId: senderId,
      conversationId: conversationId,
      timestamp: currentTime,
      sequenceNumber: sequenceNumber,
      vectorClock: new Map(this.vectorClock), # Copy current vector clock
      lamportTimestamp: this.calculateLamportTimestamp(currentTime),
      causalDependencies: this.extractCausalDependencies(message)
    }

    return orderingInfo

  function canProcessImmediately(message, orderingInfo, conversationId):
    # Check if all causal dependencies are satisfied
    for dependency in orderingInfo.causalDependencies:
      if not this.hasDependency(dependency, conversationId):
        return false

    # Check if this is the next expected message in sequence
    expectedSequence = this.getNextExpectedSequence(conversationId)
    if orderingInfo.sequenceNumber !== expectedSequence:
      return false

    return true

  function bufferMessage(message, orderingInfo, conversationId):
    # Add to buffer
    if not this.messageBuffer.has(conversationId):
      this.messageBuffer.set(conversationId, new PriorityQueue())

    buffer = this.messageBuffer.get(conversationId)
    buffer.enqueue({
      message: message,
      orderingInfo: orderingInfo,
      bufferedAt: Date.now()
    }, orderingInfo.sequenceNumber)

    # Set timeout to process buffered messages
    setTimeout(() => {
      this.processPendingMessages(conversationId)
    }, this.config.maxWaitTime)
```

```
    return { processed: false, reason: 'buffered', waitingFor: this.getMissingDependenci

  function processImmediately(message, orderingInfo, conversationId):
    # Process the message
    processedMessage = this.processMessage(message, orderingInfo)

    # Mark as processed
    this.markAsProcessed(orderingInfo)

    # Check buffer for now-processable messages
    this.processPendingMessages(conversationId)

    return { processed: true, message: processedMessage, orderingInfo: orderingInfo }

  function processPendingMessages(conversationId):
    buffer = this.messageBuffer.get(conversationId)

    if not buffer or buffer.isEmpty():
      return

    processedCount = 0

    while not buffer.isEmpty():
      nextMessage = buffer.peek()

      if this.canProcessImmediately(nextMessage.message, nextMessage.orderingInfo, conve
        # Process the message
        bufferedMessage = buffer.dequeue()
        this.processMessage(bufferedMessage.message, bufferedMessage.orderingInfo)
        this.markAsProcessed(bufferedMessage.orderingInfo)
        processedCount++
      else:
        break # Can't process next message yet

    # Log processing statistics
    if processedCount > 0:
      this.logMessageProcessing(conversationId, processedCount)
```

2. Real-time Presence Management Algorithm

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Purpose: Track and broadcast user presence status efficiently while minimizing network overhead and maintaining accuracy.

Hierarchical Presence System:

```
PresenceConfig = {
  presenceStates: ['online', 'away', 'busy', 'offline'],
  timeouts: {
    awayTimeout: 300000,        # 5 minutes
    offlineTimeout: 1800000,    # 30 minutes
    heartbeatInterval: 30000    # 30 seconds
  },

  broadcastStrategy: 'selective',  # 'broadcast_all', 'selective', 'subscription_based'
  aggregationWindow: 5000,         # 5 seconds
  presenceHistory: true,
  locationTracking: false
}

class PresenceManager:
  constructor(config):
    this.config = config
    this.userPresence = new Map()         # userId -> presence info
    this.presenceSubscriptions = new Map() # userId -> Set of subscribers
    this.heartbeatTimers = new Map()      # userId -> timer
    this.presenceUpdates = new BatchProcessor()

  function updatePresence(userId, presenceData, connectionInfo):
    currentTime = Date.now()
    previousPresence = this.userPresence.get(userId)

    # Create new presence record
    newPresence = {
      userId: userId,
      status: presenceData.status || 'online',
      lastSeen: currentTime,
      lastActivity: presenceData.lastActivity || currentTime,
      device: connectionInfo.device,
      location: presenceData.location,
      customStatus: presenceData.customStatus,

      # Connection metadata
      connectionId: connectionInfo.connectionId,
      ipAddress: connectionInfo.ipAddress,
      userAgent: connectionInfo.userAgent,

      # Presence history
      previousStatus: previousPresence?.status,
      statusChangedAt: previousPresence?.status !== presenceData.status ? currentTime :
    }

    # Store updated presence
    this.userPresence.set(userId, newPresence)

    # Reset heartbeat timer
    this.resetHeartbeatTimer(userId)

    # Determine if broadcast is needed
    if this.shouldBroadcastPresence(previousPresence, newPresence):
      this.schedulePresenceBroadcast(userId, newPresence, previousPresence)

    return newPresence

  function shouldBroadcastPresence(previousPresence, newPresence):
    # Always broadcast status changes
    if not previousPresence or previousPresence.status !== newPresence.status:
      return true

    # Broadcast location changes if tracking enabled
    if this.config.locationTracking and previousPresence.location !== newPresence.locati
      return true

    # Broadcast custom status changes
    if previousPresence.customStatus !== newPresence.customStatus:
      return true

    # Broadcast device changes
    if previousPresence.device !== newPresence.device:
      return true

    return false

  function schedulePresenceBroadcast(userId, newPresence, previousPresence):
    presenceUpdate = {
      userId: userId,
      presence: newPresence,
      previousPresence: previousPresence,
      timestamp: Date.now()
    }

    # Add to batch processor for efficient broadcasting
    this.presenceUpdates.add(presenceUpdate)
```

```
function processBatchedPresenceUpdates(updates):
  # Group updates by subscribers for efficient delivery
  subscriberUpdates = new Map()

  for update in updates:
    subscribers = this.getPresenceSubscribers(update.userId)

    for subscriberId in subscribers:
      if not subscriberUpdates.has(subscriberId):
        subscriberUpdates.set(subscriberId, [])

      subscriberUpdates.get(subscriberId).push({
        userId: update.userId,
        status: update.presence.status,
        lastSeen: update.presence.lastSeen,
        customStatus: update.presence.customStatus,
        device: update.presence.device,
        location: this.config.locationTracking ? update.presence.location : null
      })

  # Send batched updates to each subscriber
  for [subscriberId, userUpdates] in subscriberUpdates:
    this.sendPresenceUpdates(subscriberId, userUpdates)

function resetHeartbeatTimer(userId):
  # Clear existing timer
  if this.heartbeatTimers.has(userId):
    clearTimeout(this.heartbeatTimers.get(userId))

  # Set new timer for away status
  awayTimer = setTimeout(() => {
    this.handlePresenceTimeout(userId, 'away')
  }, this.config.timeouts.awayTimeout)

  this.heartbeatTimers.set(userId, awayTimer)

  # Set timer for offline status
  offlineTimer = setTimeout(() => {
    this.handlePresenceTimeout(userId, 'offline')
  }, this.config.timeouts.offlineTimeout)

function handlePresenceTimeout(userId, timeoutType):
  currentPresence = this.userPresence.get(userId)

  if not currentPresence:
    return

  # Update presence based on timeout type
  if timeoutType === 'away' and currentPresence.status === 'online':
    this.updatePresence(userId, { status: 'away' }, currentPresence)
  else if timeoutType === 'offline':
    this.updatePresence(userId, { status: 'offline' }, currentPresence)
    this.cleanupUserSession(userId)

function subscribeToPresence(subscriberId, targetUserIds):
  for targetUserId in targetUserIds:
    if not this.presenceSubscriptions.has(targetUserId):
      this.presenceSubscriptions.set(targetUserId, new Set())

    this.presenceSubscriptions.get(targetUserId).add(subscriberId)

  # Send current presence for subscribed users
  currentPresence = targetUserIds
    .filter(userId => this.userPresence.has(userId))
    .map(userId => ({
      userId: userId,
      ...this.getPublicPresence(userId)
    }))

  return currentPresence

function getPublicPresence(userId):
  presence = this.userPresence.get(userId)

  if not presence:
    return { status: 'offline', lastSeen: null }

  return {
    status: presence.status,
    lastSeen: presence.lastSeen,
    customStatus: presence.customStatus,
    device: presence.device,
    location: this.config.locationTracking ? presence.location : null
  }
```

3. Message Delivery Guarantee Algorithm

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Purpose: Ensure reliable message delivery with different consistency levels and handle network failures gracefully.

At-Least-Once Delivery with Idempotency:

```
DeliveryConfig = {
  deliveryGuarantee: 'at_least_once',      # 'at_most_once', 'at_least_once', 'exactly_o
  maxRetries: 5,
  retryBackoff: 'exponential',             # 'linear', 'exponential', 'custom'
  ackTimeout: 30000,                       # 30 seconds

  persistenceStrategy: 'write_ahead_log',   # 'memory', 'database', 'write_ahead_log'
  batchDelivery: true,
  batchSize: 50,
  batchTimeout: 1000                       # 1 second
}

class MessageDeliveryManager:
  constructor(config):
    this.config = config
    this.pendingDeliveries = new Map()     # messageId -> delivery info
    this.deliveryLog = new WriteAheadLog()
    this.retryQueue = new PriorityQueue()
    this.acknowledgments = new Map()       # messageId -> ack status

  function deliverMessage(message, recipients, deliveryOptions):
    deliveryId = generateDeliveryId()
    deliveryTimestamp = Date.now()

    # Create delivery record
    deliveryRecord = {
      deliveryId: deliveryId,
      messageId: message.id,
      senderId: message.senderId,
      recipients: recipients,
      message: message,
      createdAt: deliveryTimestamp,
      attempts: 0,
      deliveryOptions: deliveryOptions,
      status: 'pending'
    }

    # Persist delivery record
    this.deliveryLog.append(deliveryRecord)
    this.pendingDeliveries.set(deliveryId, deliveryRecord)
    # Start delivery process
    this.executeDelivery(deliveryRecord)

    return deliveryId

  function executeDelivery(deliveryRecord):
    deliveryRecord.attempts++
    deliveryRecord.lastAttemptAt = Date.now()

    # Group recipients by delivery method
    onlineRecipients = []
    offlineRecipients = []

    for recipient in deliveryRecord.recipients:
      if this.isRecipientOnline(recipient):
        onlineRecipients.push(recipient)
      else:
        offlineRecipients.push(recipient)

    # Deliver to online recipients via WebSocket
    if onlineRecipients.length > 0:
      this.deliverViaWebSocket(deliveryRecord, onlineRecipients)

    # Queue push notifications for offline recipients
    if offlineRecipients.length > 0:
      this.deliverViaPushNotification(deliveryRecord, offlineRecipients)

    # Set acknowledgment timeout
    this.setAckTimeout(deliveryRecord)

  function deliverViaWebSocket(deliveryRecord, recipients):
    deliveryPromises = []

    for recipient in recipients:
      connections = this.getActiveConnections(recipient)

      for connection in connections:
        promise = this.sendMessageToConnection(connection, deliveryRecord.message)
        deliveryPromises.push(promise)

    # Handle delivery results
    Promise.allSettled(deliveryPromises).then(results => {
      this.handleWebSocketDeliveryResults(deliveryRecord, recipients, results)
    })
```

```
function sendMessageToConnection(connection, message):
  return new Promise((resolve, reject) => {
    # Prepare message payload
    payload = {
      type: 'message',
      messageId: message.id,
      conversationId: message.conversationId,
      senderId: message.senderId,
      content: message.content,
      timestamp: message.timestamp,
      metadata: message.metadata
    }

    # Send with timeout
    timeoutId = setTimeout(() => {
      reject(new Error('Delivery timeout'))
    }, this.config.ackTimeout)

    connection.send(JSON.stringify(payload), (error) => {
      clearTimeout(timeoutId)

      if error:
        reject(error)
      else:
        resolve(connection.id)
    })
  })

function handleAcknowledgment(messageId, recipientId, ackType):
  # Find delivery record
  deliveryRecord = this.findDeliveryByMessage(messageId)

  if not deliveryRecord:
    return { success: false, reason: 'delivery_not_found' }

  # Record acknowledgment
  if not this.acknowledgments.has(messageId):
    this.acknowledgments.set(messageId, new Map())

  ackMap = this.acknowledgments.get(messageId)
  ackMap.set(recipientId, {
    type: ackType,
    timestamp: Date.now(),
    acknowledged: true
  })
  # Check if all recipients have acknowledged
  if this.isFullyAcknowledged(deliveryRecord):
    this.completeDelivery(deliveryRecord)

  return { success: true, deliveryId: deliveryRecord.deliveryId }

function handleDeliveryFailure(deliveryRecord, error):
  deliveryRecord.lastError = error
  deliveryRecord.status = 'failed'

  # Check if we should retry
  if deliveryRecord.attempts < this.config.maxRetries:
    # Calculate retry delay
    retryDelay = this.calculateRetryDelay(deliveryRecord.attempts)

    # Schedule retry
    setTimeout(() => {
      this.executeDelivery(deliveryRecord)
    }, retryDelay)

    deliveryRecord.status = 'retrying'
  else:
    # Max retries exceeded - mark as permanently failed
    deliveryRecord.status = 'permanently_failed'
    this.handlePermanentFailure(deliveryRecord)

function calculateRetryDelay(attemptNumber):
  switch this.config.retryBackoff:
    case 'linear':
      return attemptNumber * 1000 # 1s, 2s, 3s, ...
    case 'exponential':
      return Math.pow(2, attemptNumber - 1) * 1000 # 1s, 2s, 4s, 8s, ...
    case 'custom':
      return this.customRetryDelay(attemptNumber)
    default:
      return 1000 # 1 second default

function isFullyAcknowledged(deliveryRecord):
  ackMap = this.acknowledgments.get(deliveryRecord.messageId)

  if not ackMap:
    return false

  # Check if all recipients have acknowledged
```

```
    for recipient in deliveryRecord.recipients:
      if not ackMap.has(recipient) or not ackMap.get(recipient).acknowledged:
        return false

    return true

  function completeDelivery(deliveryRecord):
    deliveryRecord.status = 'delivered'
    deliveryRecord.completedAt = Date.now()

    # Remove from pending deliveries
    this.pendingDeliveries.delete(deliveryRecord.deliveryId)

    # Update delivery log
    this.deliveryLog.markCompleted(deliveryRecord.deliveryId)

    # Notify sender of successful delivery
    this.notifyDeliveryComplete(deliveryRecord)
```

4. File and Media Sharing Algorithm

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Purpose: Handle file uploads, processing, and sharing with support for multiple formats, compression, and secure access.

Progressive File Upload with Chunking:

```
FileServiceConfig = {
  maxFileSize: 104857600,          # 100MB
  allowedTypes: ['image', 'video', 'audio', 'document'],
  chunkSize: 1048576,              # 1MB chunks

  processing: {
    imageCompression: true,
    videoTranscoding: true,
    thumbnailGeneration: true,
    virusScanning: true
  },

  storage: {
    provider: 'aws_s3',            # 'aws_s3', 'google_cloud', 'azure'
    encryption: true,
    cdnEnabled: true,
    redundancy: 3
  }
}

class FileService:
  constructor(config):
    this.config = config
    this.uploadSessions = new Map()        # sessionId -> upload info
    this.fileProcessor = new FileProcessor()
    this.storageProvider = new StorageProvider(config.storage)
    this.cdnManager = new CDNManager()

  function initiateFileUpload(userId, conversationId, fileMetadata):
    # Validate file metadata
    validation = this.validateFileUpload(fileMetadata)
    if not validation.valid:
      return { success: false, errors: validation.errors }

    # Create upload session
    uploadSession = {
      sessionId: generateSessionId(),
      userId: userId,
      conversationId: conversationId,
      fileName: fileMetadata.fileName,
      fileSize: fileMetadata.fileSize,
      mimeType: fileMetadata.mimeType,

      # Upload progress
      uploadedChunks: new Set(),
      totalChunks: Math.ceil(fileMetadata.fileSize / this.config.chunkSize),
      uploadedBytes: 0,

      # Processing state
      status: 'uploading',
      createdAt: Date.now(),
      expiresAt: Date.now() + 3600000,     # 1 hour expiry

      # Security
      uploadToken: generateSecureToken(),
      ipAddress: fileMetadata.clientIP
    }

    this.uploadSessions.set(uploadSession.sessionId, uploadSession)

    return {
      success: true,
      sessionId: uploadSession.sessionId,
      uploadToken: uploadSession.uploadToken,
      chunkSize: this.config.chunkSize,
      totalChunks: uploadSession.totalChunks
    }

  function uploadFileChunk(sessionId, chunkIndex, chunkData, uploadToken):
    uploadSession = this.uploadSessions.get(sessionId)

    # Validate upload session
    if not uploadSession or uploadSession.uploadToken !== uploadToken:
      return { success: false, error: 'invalid_session' }

    if Date.now() > uploadSession.expiresAt:
      return { success: false, error: 'session_expired' }

    # Validate chunk
    if chunkIndex >= uploadSession.totalChunks or uploadSession.uploadedChunks.has(chunk
      return { success: false, error: 'invalid_chunk' }

    # Store chunk temporarily
    chunkPath = this.storeTemporaryChunk(sessionId, chunkIndex, chunkData)

    # Update upload progress
    uploadSession.uploadedChunks.add(chunkIndex)
    uploadSession.uploadedBytes += chunkData.length

    # Check if upload is complete
    if uploadSession.uploadedChunks.size === uploadSession.totalChunks:
      this.completeFileUpload(uploadSession)

    return {
      success: true,
      uploadedChunks: uploadSession.uploadedChunks.size,
      totalChunks: uploadSession.totalChunks,
      progress: uploadSession.uploadedBytes / uploadSession.fileSize
    }

  function completeFileUpload(uploadSession):
    uploadSession.status = 'assembling'

    # Assemble file from chunks
    assembledFile = this.assembleFileFromChunks(uploadSession)

    # Verify file integrity
    if not this.verifyFileIntegrity(assembledFile, uploadSession):
      uploadSession.status = 'failed'
      return

    # Start file processing pipeline
    this.processUploadedFile(uploadSession, assembledFile)

  function processUploadedFile(uploadSession, fileData):
    uploadSession.status = 'processing'

    processingTasks = []

    # Virus scanning
    if this.config.processing.virusScanning:
      processingTasks.push(this.scanFileForViruses(fileData))

    # Generate thumbnails for images/videos
    if this.shouldGenerateThumbnail(uploadSession.mimeType):
      processingTasks.push(this.generateThumbnail(fileData, uploadSession.mimeType))

    # Compress images
    if this.config.processing.imageCompression and uploadSession.mimeType.startsWith('im
      processingTasks.push(this.compressImage(fileData))

    # Transcode videos
    if this.config.processing.videoTranscoding and uploadSession.mimeType.startsWith('vi
      processingTasks.push(this.transcodeVideo(fileData))

    # Execute processing tasks
    Promise.all(processingTasks).then(results => {
      this.finalizeFileUpload(uploadSession, fileData, results)
    }).catch(error => {
      this.handleProcessingError(uploadSession, error)
    })

  function finalizeFileUpload(uploadSession, fileData, processingResults):
    # Store file in permanent storage
    storageResult = this.storageProvider.store(fileData, {
      userId: uploadSession.userId,
      conversationId: uploadSession.conversationId,
      fileName: uploadSession.fileName,
      mimeType: uploadSession.mimeType,
      encryption: this.config.storage.encryption
    })
```

```
# Create file record
fileRecord = {
  fileId: generateFileId(),
  sessionId: uploadSession.sessionId,
  userId: uploadSession.userId,
  conversationId: uploadSession.conversationId,

  # File metadata
  fileName: uploadSession.fileName,
  fileSize: uploadSession.fileSize,
  mimeType: uploadSession.mimeType,

  # Storage information
  storageLocation: storageResult.location,
  storagePath: storageResult.path,
  checksumMD5: calculateMD5(fileData),
  checksumSHA256: calculateSHA256(fileData),

  # Processing results
  thumbnailUrl: this.extractThumbnailUrl(processingResults),
  compressedVersions: this.extractCompressedVersions(processingResults),
  transcodedVersions: this.extractTranscodedVersions(processingResults),

  # Security and access
  accessToken: generateFileAccessToken(),
  publicUrl: this.generatePublicUrl(storageResult.path),

  # Metadata
  createdAt: Date.now(),
  uploadedAt: Date.now(),
  expiresAt: null  # Set based on conversation retention policy
}

# Save file record to database
this.saveFileRecord(fileRecord)

# Update upload session
uploadSession.status = 'completed'
uploadSession.fileId = fileRecord.fileId
uploadSession.completedAt = Date.now()

# Notify completion
this.notifyFileUploadComplete(uploadSession, fileRecord)

# Cleanup temporary files
```

```
    this.cleanupTemporaryFiles(uploadSession.sessionId)

  function generateSecureFileUrl(fileId, userId, accessDuration = 3600000):
    fileRecord = this.getFileRecord(fileId)

    if not fileRecord:
      return null

    # Check access permissions
    if not this.canUserAccessFile(userId, fileRecord):
      return null

    # Generate time-limited signed URL
    signedUrl = this.storageProvider.generateSignedUrl(fileRecord.storagePath, {
      expiresIn: accessDuration,
      userId: userId,
      fileId: fileId
    })

    return {
      url: signedUrl,
      expiresAt: Date.now() + accessDuration,
      thumbnailUrl: fileRecord.thumbnailUrl,
      metadata: {
        fileName: fileRecord.fileName,
        fileSize: fileRecord.fileSize,
        mimeType: fileRecord.mimeType
      }
    }
```

5. Chat Analytics and Insights Algorithm

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Purpose: Analyze chat patterns, user engagement, and conversation insights while maintaining privacy and providing actionable data.

Real-time Analytics Processing:

```
AnalyticsConfig = {
  metricsCollection: {
    messageMetrics: true,
    userEngagement: true,
    conversationInsights: true,
    performanceMetrics: true
  },

  privacySettings: {
    anonymizeData: true,
    dataRetention: 2592000000,     # 30 days
    excludeSensitiveContent: true,
    consentRequired: true
  },

  realTimeProcessing: {
    enabled: true,
    batchSize: 1000,
    processingInterval: 30000      # 30 seconds
  }
}

class ChatAnalyticsEngine:
  constructor(config):
    this.config = config
    this.metricsCollector = new MetricsCollector()
    this.analyticsProcessor = new AnalyticsProcessor()
    this.privacyManager = new PrivacyManager()
    this.insightsGenerator = new InsightsGenerator()

  function processMessageEvent(messageEvent):
    if not this.hasUserConsent(messageEvent.userId):
      return # Skip processing without consent

    # Extract analytics data
    analyticsData = this.extractAnalyticsData(messageEvent)

    # Apply privacy filters
    sanitizedData = this.privacyManager.sanitize(analyticsData)

    # Process metrics
    this.processMessageMetrics(sanitizedData)
    this.processEngagementMetrics(sanitizedData)
    this.processConversationMetrics(sanitizedData)

    # Store for batch processing
    this.metricsCollector.add(sanitizedData)

  function extractAnalyticsData(messageEvent):
    return {
      # Message metrics
      messageId: messageEvent.messageId,
      messageLength: messageEvent.content.length,
      messageType: this.classifyMessageType(messageEvent.content),
      hasAttachment: messageEvent.attachments?.length > 0,

      # User metrics (anonymized)
      userHash: this.hashUserId(messageEvent.userId),
      conversationHash: this.hashConversationId(messageEvent.conversationId),

      # Temporal metrics
      timestamp: messageEvent.timestamp,
      timeOfDay: new Date(messageEvent.timestamp).getHours(),
      dayOfWeek: new Date(messageEvent.timestamp).getDay(),

      # Engagement metrics
      responseTime: this.calculateResponseTime(messageEvent),
      conversationDepth: this.getConversationDepth(messageEvent.conversationId),

      # Performance metrics
      deliveryTime: messageEvent.deliveryTime,
      processingTime: messageEvent.processingTime
    }

  function generateConversationInsights(conversationId, timeRange):
    messages = this.getConversationMessages(conversationId, timeRange)

    if messages.length === 0:
      return null

    insights = {
      conversationId: conversationId,
      timeRange: timeRange,
      generatedAt: Date.now(),

      # Basic metrics
      totalMessages: messages.length,
      uniqueParticipants: this.countUniqueParticipants(messages),
      averageMessageLength: this.calculateAverageMessageLength(messages),

      # Engagement metrics
      engagementScore: this.calculateEngagementScore(messages),
      responseTimeMetrics: this.calculateResponseTimeMetrics(messages),
      participationDistribution: this.calculateParticipationDistribution(messages),

      # Content analysis
      topicAnalysis: this.analyzeTopics(messages),
      sentimentAnalysis: this.analyzeSentiment(messages),
      keywordExtraction: this.extractKeywords(messages),

      # Temporal patterns
      activityPatterns: this.analyzeActivityPatterns(messages),
      peakHours: this.identifyPeakHours(messages),

      # Quality metrics
      conversationHealth: this.assessConversationHealth(messages)
    }

    return insights

  function calculateEngagementScore(messages):
    if messages.length === 0:
      return 0

    factors = {
      messageFrequency: this.calculateMessageFrequency(messages),
      responseRate: this.calculateResponseRate(messages),
      messageDepth: this.calculateAverageMessageDepth(messages),
      participantRetention: this.calculateParticipantRetention(messages),
      interactionTypes: this.analyzeInteractionTypes(messages)
    }

    # Weighted engagement score
    engagementScore = (
      factors.messageFrequency * 0.25 +
      factors.responseRate * 0.25 +
      factors.messageDepth * 0.2 +
      factors.participantRetention * 0.2 +
      factors.interactionTypes * 0.1
    )

    return Math.min(Math.max(engagementScore, 0), 1) # Clamp between 0 and 1

  function analyzeTopics(messages):
    # Extract content for topic analysis
    textContent = messages
      .map(msg => msg.content)
      .filter(content => content && content.length > 0)
      .join(' ')

    if textContent.length === 0:
      return []

    # Use NLP for topic extraction
    topics = this.nlpProcessor.extractTopics(textContent, {
      minTopicWords: 3,
      maxTopics: 10,
      confidenceThreshold: 0.6
    })

    return topics.map(topic => ({
      topic: topic.words.join(', '),
      confidence: topic.confidence,
      frequency: topic.frequency,
      firstMention: this.findFirstTopicMention(messages, topic.words),
      trending: this.isTopicTrending(topic, messages)
    }))

  function analyzeSentiment(messages):
    sentimentData = messages.map(message => {
      sentiment = this.nlpProcessor.analyzeSentiment(message.content)
      return {
        messageId: message.id,
        sentiment: sentiment.label,      # 'positive', 'negative', 'neutral'
        confidence: sentiment.confidence,
        score: sentiment.score           # -1 to 1
      }
    })

    # Calculate overall sentiment metrics
    overallSentiment = {
      averageScore: sentimentData.reduce((sum, s) => sum + s.score, 0) / sentimentData.l
      sentimentDistribution: this.calculateSentimentDistribution(sentimentData),
      sentimentTrend: this.calculateSentimentTrend(sentimentData),
      emotionalHighlights: this.identifyEmotionalHighlights(sentimentData)
    }

    return overallSentiment

  function generateUserEngagementReport(userId, timeRange):
    userEvents = this.getUserEvents(userId, timeRange)

    if userEvents.length === 0:
      return null

    report = {
      userId: this.hashUserId(userId),
      timeRange: timeRange,
      reportGeneratedAt: Date.now(),

      # Activity metrics
      totalMessages: userEvents.filter(e => e.type === 'message_sent').length,
      totalConversations: this.countUniqueConversations(userEvents),
      activeHours: this.calculateActiveHours(userEvents),
      averageSessionDuration: this.calculateAverageSessionDuration(userEvents),

      # Engagement patterns
      messageFrequencyPattern: this.analyzeMessageFrequency(userEvents),
      conversationInitiation: this.calculateConversationInitiation(userEvents),
      responseTimePattern: this.analyzeResponseTimePattern(userEvents),

      # Content analysis
      communicationStyle: this.analyzeCommunicationStyle(userEvents),
      topTopics: this.extractUserTopTopics(userEvents),
      emojiUsage: this.analyzeEmojiUsage(userEvents),

      # Network analysis
      communicationNetwork: this.buildCommunicationNetwork(userEvents),
      influenceScore: this.calculateInfluenceScore(userEvents),

      # Behavioral insights
      onlinePresencePattern: this.analyzePresencePattern(userId, timeRange),
      deviceUsagePattern: this.analyzeDeviceUsage(userEvents),
      preferredCommunicationTimes: this.identifyPreferredTimes(userEvents)
    }

    return report
```

Performance Optimizations

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WebSocket Connection Scaling

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Connection Pool Management:

```
WebSocketOptimization = {
  connectionPooling: {
    maxConnectionsPerServer: 10000,
    loadBalancing: 'least_connections',
    stickySession: true
  },

  messageCompression: {
    enabled: true,
    algorithm: 'deflate',
    threshold: 1024  # Compress messages > 1KB
  },

  batchingStrategy: {
    enabled: true,
    maxBatchSize: 10,
    maxWaitTime: 50  # 50ms
  }
}
```

Database Optimization

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Message Storage Strategy: - Time-based partitioning - Read replicas for analytics - Message archiving for old conversations - Efficient indexing on conversation_id, timestamp

Security Considerations

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Chat Security Framework

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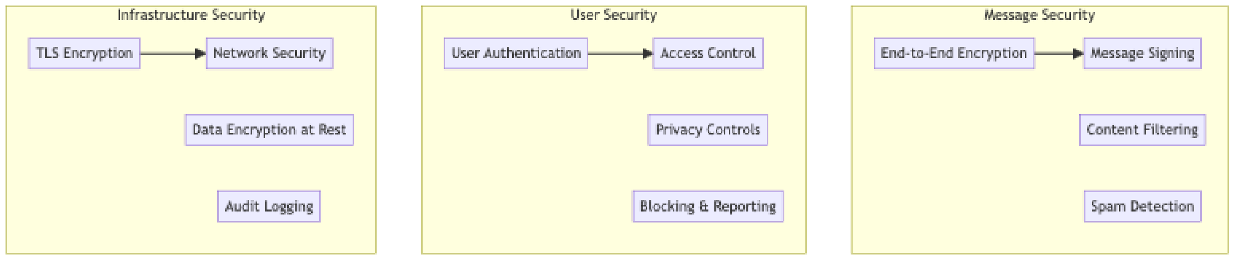

Testing Strategy

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Load Testing

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Concurrent Connection Testing: - WebSocket connection limits (100K+ concurrent) - Message throughput testing - Database performance under load - Real-time delivery latency

Reliability Testing

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Fault Tolerance Testing: - Network partition handling - Server failure scenarios - Message delivery guarantees - Data consistency verification

Trade-offs and Considerations

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Consistency vs Availability

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- **Message ordering**: Strong consistency vs availability
- **Presence updates**: Real-time accuracy vs system performance
- **Delivery guarantees**: Reliability vs latency

- **Cross-device sync**: Consistency vs battery/network usage

Privacy vs Features

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- **Message analytics**: Insights vs privacy protection
- **Read receipts**: Transparency vs privacy
- **Presence information**: Social features vs privacy
- **Message history**: Convenience vs data retention

Scalability vs Cost

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- **Real-time delivery**: Low latency vs infrastructure cost
- **Message storage**: Durability vs storage expenses
- **Global presence**: Worldwide availability vs operational complexity
- **Rich media support**: Feature richness vs bandwidth/storage costs

This real-time chat messaging backend provides a comprehensive foundation for scalable messaging with features like reliable message delivery, real-time presence, file sharing, ordering guarantees, and analytics while maintaining high performance, security, and user privacy standards.