Mastering System Design

Design a Chat Application (aka WhatsApp)

What are we building? - And Functional Requirements

- We’re designing a real-time chat application like WhatsApp.
- Functional Requirements
  a. 1-to-1 and group messaging
  b. Typing indicators and online status
  c. Media support (images, videos, documents)
  d. Delivery and read receipts
  e. Multi-device support with sync

Non-Functional Requirements

- Sub-second message delivery
- High availability & fault tolerance
- End-to-end encryption
- Scalable to millions of users
- Smooth UX even on poor networks

Constraints & Challenges

- 🔁 Message Ordering & Delivery Guarantees
  - Ensure no duplicates, no lost messages, and correct order, even under retries or reconnections.
- 📶 Unreliable Networks
  - Mobile users may frequently disconnect; we need robust retry, buffering, and sync mechanisms.
- 🔐 Security & Privacy
  - End-to-end encryption must be seamless, with no access to message content by servers.
- ⚡ Latency Expectations
  - Sub-second message delivery is expected, regardless of load or geography.
- 👥 Presence & Sync
  - Track who's online and sync message state across all devices in near real-time.
- 📈 High Scale
  - Millions of concurrent users, chatrooms, and messages per second; we must scale horizontally and efficiently.

Estimating Scale

- We begin with a few rough assumptions to get a sense of expected load:
  - Active users/day: 100 million
  - Average messages/user/day: 50
  - Messages/day: 100M × 50 = 5 billion messages/day
  - Peak traffic multiplier: 3× during global events
  - Concurrent connections: 20–30 million users online at peak

Identifying System Bottlenecks and Challenges

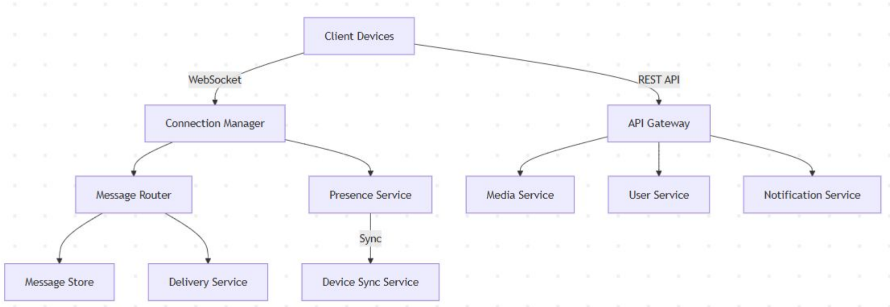
1. Message Ingestion & Fanout
    a. Fanout to multiple recipients or devices causes exponential delivery load
    b. Must queue, buffer, and batch smartly (e.g., Kafka, Redis Streams)
2. Presence Updates
    a. Real-time online/offline tracking is chatty and high frequency
    b. Use Pub/Sub patterns and efficient TTL-based caching
3. Delivery Acknowledgments
    a. Each sent/read receipt adds more writes — can overload databases
    b. Needs fast, write-optimized storage like Cassandra or DynamoDB
4. Sync Across Devices
    a. Every message must sync across all logged-in devices
    b. Requires a device registry and smart deduplication
5. Storage & Retrieval
    a. Billions of messages stored with search capability
    b. Must partition smartly and use append-friendly stores
6. Encryption & Security
    a. End-to-end encryption adds CPU cost and complexity
    b. Key exchange and secure metadata handling must scale too

Key Bottleneck: Real-Time Delivery (WebSockets)

- Real-time delivery is fundamental to chat systems — users expect messages to appear instantly. This means:
- Persistent connections need to be maintained for millions of users using WebSockets
- Load balancers and application servers must handle long-lived connections
- Need for connection management service: track connected users, devices, and routing
- Risk: connection churn, network drops, or mobile limitations (e.g., background app states)
- Why it's a bottleneck:
  - Handling millions of concurrent WebSocket connections requires optimized infra, horizontal scaling, and careful connection lifecycle management.

High-Level Architecture Overview and Key components

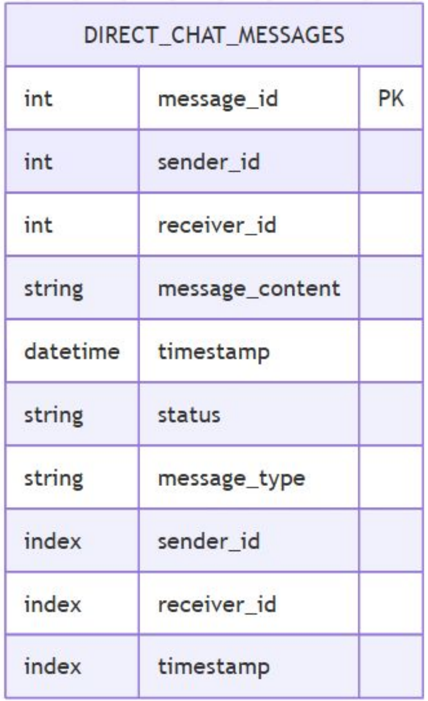
- Connection Manager (WebSocket Service):
  - Manages persistent WebSocket connections, delivers real-time messages, and tracks user/device sessions.
- Chat Service:
  - Core business logic for sending, receiving, storing messages, and managing delivery status and history.
- Presence Service:
  - Tracks online/offline status, typing indicators, and syncs across user devices using pub-sub or Redis.
- Notification Service:
  - Handles fallback notifications (e.g., push, SMS) when recipients are offline or WebSocket delivery fails.
- Media Service:
  - Manages upload and retrieval of media files like images, videos, and attachments using object storage.
- Auth & User Service:
  - Responsible for authentication, user profile management, and device binding.
- Storage Layer:
  - Backing stores for messages, presence, media metadata, and delivery receipts — optimized for high write throughput.
- Group Service:
  - Group Management: Handles group creation, deletion, and membership management (add/remove users).



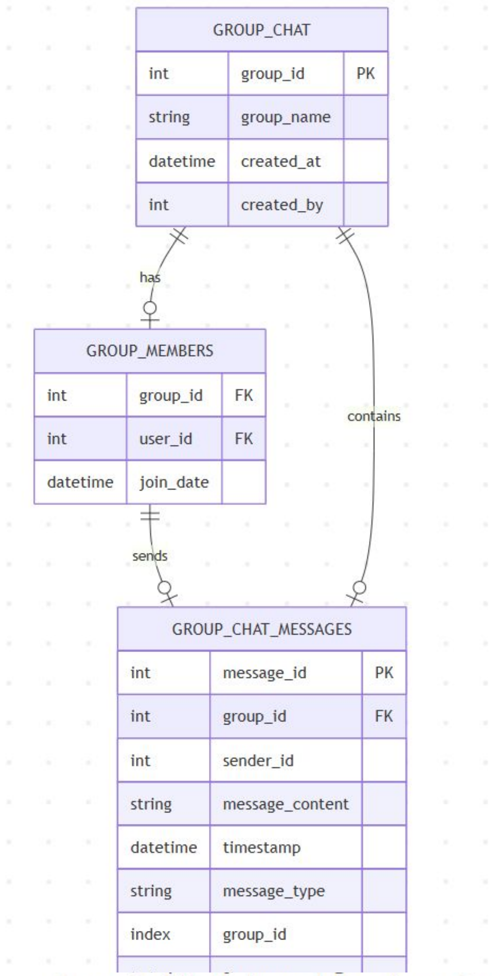
Real-Time Connection Manager (WebSocket Service)

- Maintains long-lived WebSocket connections per user and device.
- Handles message routing between senders and recipients.
- Integrates with Presence and Chat services for sync and state management.
- Supports scale-out using sticky sessions, Redis pub-sub, or message queues.
- Ensures delivery acknowledgments, retries, and device-level delivery tracking.

DB Schema for Direct Chat



DIRECT_CHAT_MESSAGES		
int	message_id	PK
int	sender_id	
int	receiver_id	
string	message_content	
datetime	timestamp	
string	status	
string	message_type	
index	sender_id	
index	receiver_id	
index	timestamp	



GROUP_CHAT		
int	group_id	PK
string	group_name	
datetime	created_at	
int	created_by	

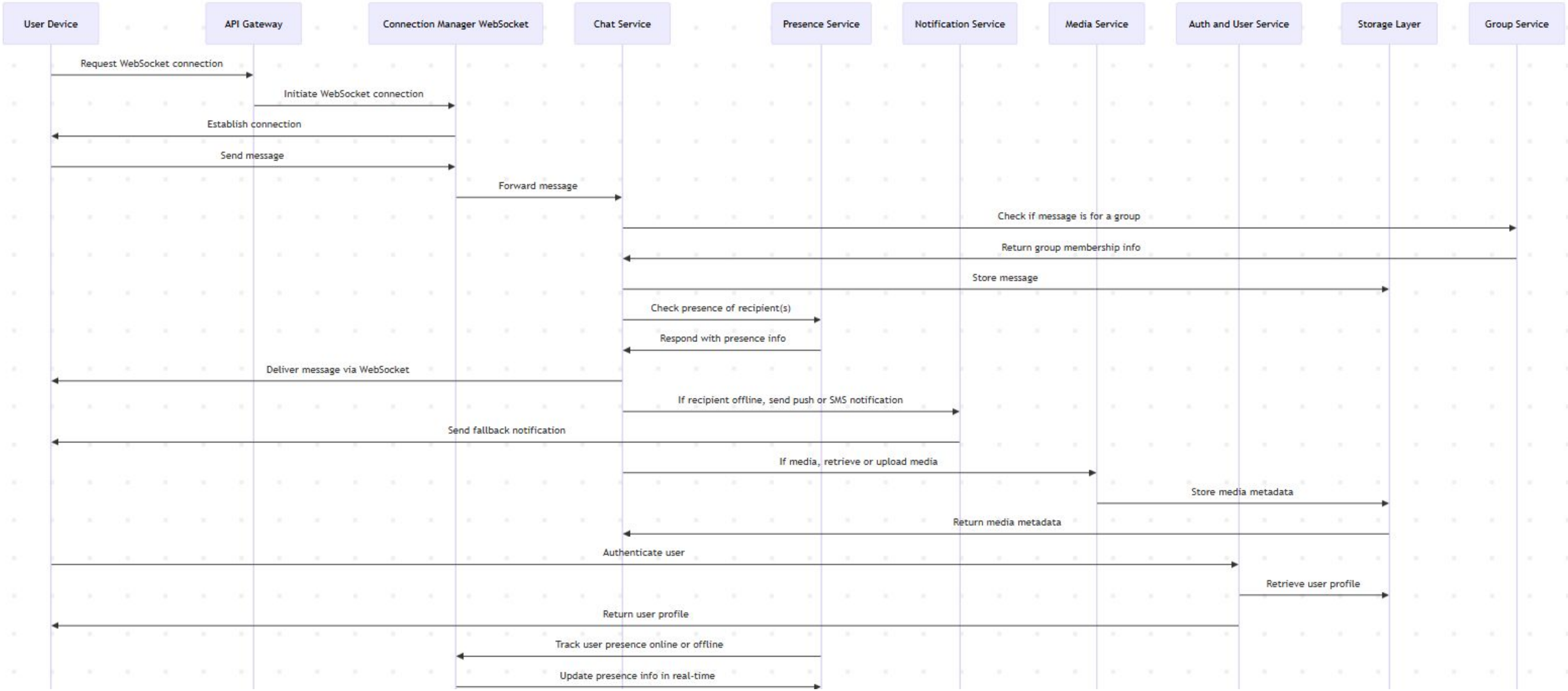
GROUP_MEMBERS		
int	group_id	FK
int	user_id	FK
datetime	join_date	

GROUP_CHAT_MESSAGES		
int	message_id	PK
int	group_id	FK
int	sender_id	
string	message_content	
datetime	timestamp	
string	message_type	
index	group_id	

How Chat & Group Chat Services Use Connection Manager for Real-Time Messaging

- Direct Chat:
  - Sender sends a message to the Chat Service with the recipient's user ID.
  - The Chat Service then sends the message to the Connection Manager.
  - Connection Manager looks up the recipient's active WebSocket connection and forwards the message to the corresponding WebSocket server.
  - The Receiver receives the message in real-time.
- Group Chat:
  - Sender sends a message to the Group Chat Service with the group ID and message content.
  - The Group Chat Service queries the Connection Manager, which looks up all active WebSocket connections for users in that group via the Group Members table.
  - The Connection Manager forwards the message to all group members' active WebSocket connections.
  - All group members receive the message simultaneously.

Chat Application - Message Flow & Sequence Diagram



User Device

API Gateway

Connection Manager WebSocket

Chat Service

Presence Service

Notification Service

Media Service

Auth and User Service

Storage Layer

Group Service

Request WebSocket connection

Initiate WebSocket connection

Establish connection

Send message

Forward message

Check if message is for a group

Return group membership info

Store message

Check presence of recipient(s)

Respond with presence info

Deliver message via WebSocket

If recipient offline, send push or SMS notification

Send fallback notification

If media, retrieve or upload media

Store media metadata

Return media metadata

Authenticate user

Retrieve user profile

Return user profile

Track user presence online or offline

Update presence info in real-time

Step 3: High-Level Design: Services, APIs & Communication

API Design – WebSocket + REST

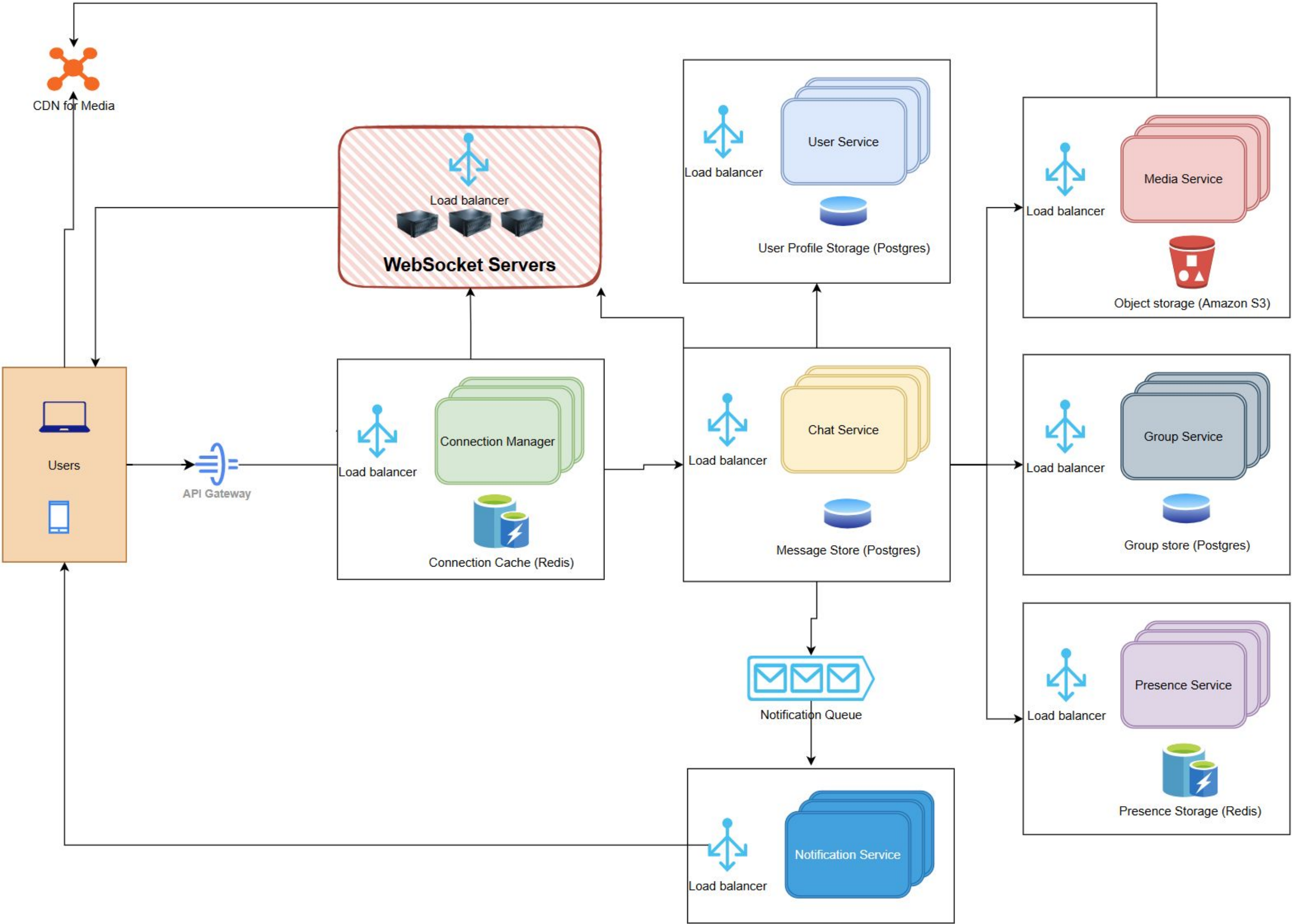
- 🔌WebSocket Communication (Real-Time)
  - connect: Initiates persistent connection with access token and user metadata.
  - send_message: JSON payload with recipient ID, message content, timestamp, type.
  - message_ack: Acknowledgment from client upon delivery/read.
  - typing_indicator: Optional message indicating typing state.
- 🔁 REST APIs (Non-Real-Time Needs)
  - GET /messages?userId=&conversationId=
    - Fetch historical messages with pagination and filters.
  - POST /media/uploadUpload image/video/audio
    - attachments and get media URL.
  - GET /presence/{userId}
    - Fetch last seen / online status for a user.
  - POST /feedback
  - S ubmit crash reports or feedback (optional).
- 🔐 Security
  - All requests (WebSocket handshake + REST) require JWT auth.
  - Role-based access for user vs. admin endpoints.

Strategic Tech & Infra Decisions

- Tech Stack Choices:
    - Message Broker: Kafka (high-throughput) or AWS SQS (managed service)
    - Real-time Communication: WebSockets for instant messaging, leveraging SignalR (for .NET) or similar frameworks
    - Notification System: Firebase Cloud Messaging (FCM) for push notifications
    - Database: NoSQL databases (e.g., MongoDB) for fast reads and flexible schema
- Infrastructure & Deployment:
    - Deployment: Microservices on Kubernetes for scalability and management
    - Scaling: Horizontal scaling for WebSocket connections; KEDA (Kubernetes Event-Driven Autoscaling) for auto-scaling workers
    - Storage: Redis for caching active user sessions, PostgreSQL for transactional data (e.g., user settings)
- Security & Observability:
    - Authentication: OAuth2 for secure authentication across platforms
    - Logging & Monitoring: Prometheus and Grafana for real-time monitoring; CloudWatch for logs and alerts
    - High Availability: Multi-region deployment for failover; load balancing across WebSocket servers

Step 4: Making Tech & Infra Decisions Strategically

The Final Design - Chat Application


CDN for Media
Load balancer
WebSocket Servers
Users
API Gateway
Load balancer
Connection Manager
Connection Cache (Redis)
Load balancer
User Service
User Profile Storage (Postgres)
Load balancer
Chat Service
Message Store (Postgres)
Notification Queue
Load balancer
Notification Service
Load balancer
Media Service
Object storage (Amazon S3)
Load balancer
Group Service
Group store (Postgres)
Load balancer
Presence Service
Presence Storage (Redis)