Mastering System Design

Design a Cloud Storage System (Google Drive, Dropbox)

Understanding the Problem

- Allows users to upload, store, and manage files of any type.
- Keeps files synchronized across devices (desktop, mobile, web).
- Enables secure sharing and collaboration with others.
- Handles massive scale (millions of users, petabytes of data).
- Maintains version history and supports file recovery.

Functional Requirements

- File Upload & Download
  - Users can upload files of any type and retrieve them on-demand.
- Multi-Device Sync
  - Automatically sync files across web, mobile, and desktop clients.
- File Organization
  - Support folders, nested directories, and tagging.
- Sharing & Collaboration
  - Public/private links, editable access, shared folders.
- File Versioning
  - Maintain previous versions and allow rollback.
- Soft Delete & Restore
  - Trash bin with restore option before permanent deletion.

🔍 *Focus on features that users expect from platforms like Google Drive or Dropbox.*

Non-Functional Requirements

- Scalability
  - Must support millions of users and petabytes of data.
- High Availability & Durability
  - 99.999999999% durability (aka "eleven nines") for files.
- Low Latency
  - Fast uploads/downloads for small & large files.
- Security
  - End-to-end encryption, secure sharing, access control.
- Cost Efficiency
  - Optimize storage and bandwidth usage.
- Observability & Monitoring
  - Track usage, errors, sync delays, API failures.

⚠️ These qualities shape your architectural choices and trade-offs later.

Assumptions and Constraints

- ✅Key Assumptions (impacting architecture):
  - 📁 Files can be large (up to 5 GB) → requires chunked uploads
  - 🌐 Users access from multiple devices → real-time sync essential
  - 💾 Cloud object storage will be used → separation of metadata & file content
  - 👤 Authentication & user identity is handled externally → we focus on storage layer
- 🚧 Core Constraints (that shape the system):
  - 📶 Uploads must be resumable → chunk tracking, session management
  - 🔄 File sync latency < 5 seconds → event-driven updates, push mechanisms
  - 💰 Storage must be cost-efficient → deduplication & lifecycle policies
  - 🔐 Fine-grained access control required → permission model and ACL support

Estimating Scale – Users, Listings, and Bookings

- ✅ Key Metrics (Initial + Growth Projections):
  - 👥 Users: 10M active users
  - 📁 Average files/user: 500
  - 💾 Total stored files: ~5B
  - 📦 Average file size: 2MB
  - 🧠 Total data stored: ~10PB
  - 📈 Upload rate: ~2K uploads/sec (peak)
  - 🔄 Sync events: ~10K updates/sec (peak)
- 📌 Implication:
  - Scale requires object storage for durability, distributed metadata service, and horizontal scalability in sync and notification pipelines.

Understanding Access Patterns

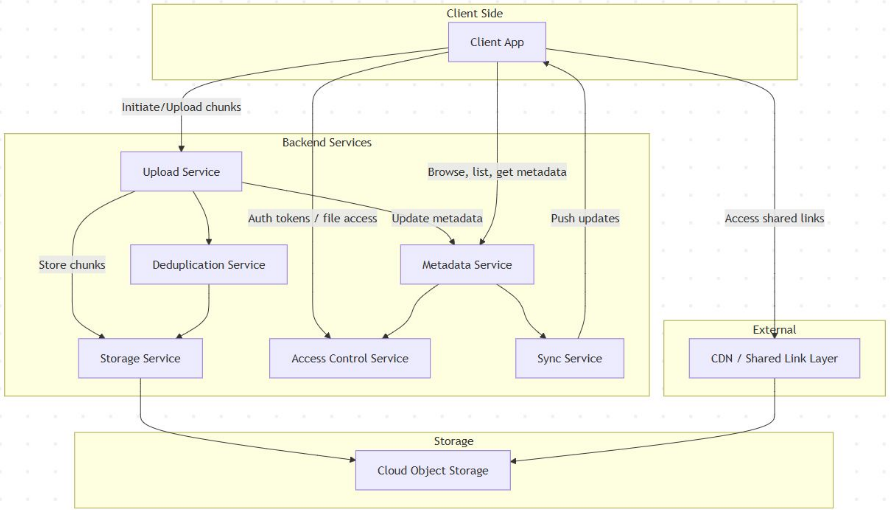
- 🔽 Write-heavy:
  - Uploads = large payloads (chunked)
  - Frequent sync updates
  - Versioning = multiple writes per file
- 🔼 Read-heavy:
  - Downloads from multiple devices
  - Folder listings & metadata reads
  - Shared link previews
- 📌 Implication:
  - Must optimize both file write flow (chunking, session mgmt) and metadata read flow (low-latency access, caching).

Identifying System Bottlenecks and Challenges

- 🚫 Single metadata DB → becomes a hotspot
- 🕒 Large file uploads → risk of failure, timeouts
- 🔁 Real-time sync → must avoid stale states, race conditions
- 🔗 Permission checks → slow file/folder access
- 📡 High volume shared links → unauthenticated access traffic
- 📌 Implication:
  - Push toward partitioned metadata, chunked resumable uploads, pub-sub sync, caching for shared/public content.

Major Components in Our Cloud Storage System

- 📤 **Upload Service**: Handles chunked/resumable uploads
- 🧾 **Metadata Service**: Stores file structure, permissions, ownership
- 🪪 **Auth Service**: Validates permissions for all operations
- 🔁 **Sync Service**: Pushes changes to connected devices in near real-time
- 💽 **Storage Service**: Interfaces with cloud object storage
- 🧠 **Deduplication Service**: Eliminates redundant file chunks
- 🗑️ **Versioning Service**: Manages previous versions and deleted files



API Design Overview

- 📤 Upload & File Management
  - POST /upload/initiate → Starts a new file upload session and returns an Upload ID
  - PUT /upload/{id}/chunk → Uploads a chunk for the given Upload ID
  - POST /upload/{id}/complete → Finalizes upload, assembles file, triggers post-processing
- 📁 File Retrieval & Metadata
  - GET /files/{fileId} → Downloads the file with access control checks
  - GET /files/{fileId}/metadata → Fetches file metadata, version history, permissions
- 🔗 Sharing & Collaboration
  - POST /files/{fileId}/share → Creates a shareable link (public/private)
  - GET /files/shared/{token} → Access file via shared link (unauthenticated access)
- 🔄 Sync & Change Tracking
  - GET /sync/updates → Streams or polls for real-time file/folder changes

✅ All APIs are secured, support idempotency, and follow RESTful principles. Uploads are resumable. Metadata is separate from file content.

How Services Communicate

- ☁️ Patterns Used:
  - REST + gRPC APIs for synchronous communication
  - Pub/Sub or message queues for:
    - Change events (for sync)
    - Post-upload processing
- Event sourcing for sync and versioning triggers
  - 📡 Real-time needs → WebSockets or long polling to push file updates

Handling Chunking for Large Files

- Why Chunking?
  - Efficient upload for large files
  - Resumable uploads to prevent data loss
  - Parallel uploads for faster transfers
- How We Handle Chunking:
  - Split files into manageable chunks (e.g., 5MB per chunk)
  - Each chunk is independently uploaded (with its own checksum)
  - Chunk metadata is tracked in the Metadata Service (upload progress, chunk ID)
  - After all chunks are uploaded, they are assembled into a single file in the Storage Service
- Chunk Management:
  - Retries if a chunk fails during upload
  - Error handling: If upload is interrupted, resume from the last successful chunk

Versioning for File Updates

- Why Versioning?
  - Preserve historical file states for rollback
  - Allow users to track changes and restore previous versions
- How We Handle Versioning:
  - File metadata stores version information (timestamps, versions)
  - Each file update triggers a new version entry in the Metadata Service
  - Version IDs for easy access to specific versions
  - Users can restore any version via a simple API call (GET /files/{fileId}/version/{versionId})
- Versioning Workflow:
  - A new file upload will generate a new version if file content differs from previous
  - Change detection: Compare chunks or file hashes to detect if file has changed

Storage Strategy

- Object Storage:
  - Store files as chunks for efficient uploads, parallelism, and resilience.
  - Ensure data replication for redundancy and availability.
- SQL vs. NoSQL for Metadata:
  - SQL for structured metadata (user data, permissions, file details).
  - NoSQL for flexible or dynamic metadata (logs, dynamic file attributes).
- Scalability & Fault Tolerance:
  - Object storage offers horizontal scalability.
  - NoSQL for fast scaling of unstructured data.

Caching Strategy

- Metadata Caching:
  - Use in-memory caches for fast access to metadata.
- File Content Caching:
  - Cache files at edge locations via a CDN for quick retrieval.
- Sync & Consistency:
  - Use event systems (e.g., queues) for real-time sync and cache invalidation.

Database Schema (Rough Overview)

- User Management:
  - SQL for structured user data and relationships.
- File Metadata:
  - SQL for structured metadata, NoSQL for flexible or dynamic attributes.
- Chunk Tracking:
  - NoSQL for chunk metadata tracking.
- File Versions:
  - SQL for relational versioning, NoSQL for scalable versioning.
- Permissions:
  - SQL for managing access control (read/write).
- Audit Logging:
  - SQL for structured logs, NoSQL for high-volume logs.

Strategic Tech & Infra Decisions

- Architecture:
  - Microservices, Containers (Docker, Kubernetes)
- Storage:
  - Object Storage for file chunks (e.g., S3, MinIO)
- Database:
  - SQL (PostgreSQL) for structured metadata.
  - NoSQL (MongoDB) for scalable metadata.
- Caching:
  - In-memory caching (e.g., Redis), CDN for content delivery
- API Gateway:
  - For request routing, security (e.g., Kong, NGINX)
- Auto-Scaling:
  - Dynamic scaling based on load

The Final Design - Cloud Storage System