Mastering System Design

Design a Search Engine (aka Google)

What Are We Building?

- Design a search engine that can:
  - Crawl and index billions of web pages
  - Serve keyword-based queries
  - Return relevant, ranked results in real-time
  - Update the index periodically for freshness
- Key Users:
  - General users performing web searches
  - Internal analytics teams querying data

Functional Requirements

- 🌐 Web Crawling : Discover and fetch web pages at scale
- 📄 Indexing : Extract text, normalize, and structure for fast querying
- 🔍 Keyword Search: Accept queries and return relevant documents
- 📈 Ranking: Score and sort results by relevance
- 🔄 Re-indexing: Periodically re-crawl for updated/fresh content

Non-Functional Requirements

- ⚡ Performance: < 200ms query response time
- 🚀 Scalability: Index billions of documents, handle 50K QPS
- 🔁 Freshness: Update index with recent changes in hours
- ☠️ Fault Tolerance: No single point of failure; retry on fetch failure
- 📦 Storage Efficiency: Compress and deduplicate massive data volumes

Key System Design Challenges

- 🌍 Crawling the Web: How to avoid duplication and rate limits?
- 🧠 Indexing: How to store & search through billions of documents fast?
- ⚖️ Relevance: How to rank results in a meaningful way?
- 📶 Scaling: How to scale search infra as usage and index size grow?
- 🔄 Freshness vs. Cost: How often should we re-crawl?

Assumptions and Constraints

- ✅ Assumptions:
  - We're focusing on publicly accessible websites (no login or dynamic JS-heavy pages).
  - Crawlers will respect robots.txt and politeness policies.
  - Query language is limited to simple keyword searches.
  - Ranking will be based on basic relevance models (TF-IDF, PageRank).
  - Users expect instantaneous results (<200ms) for top N results (e.g., 10–20).
- ⚠️ Constraints:
  - Limited bandwidth for crawling — need scheduling and deduplication.
  - Storage and indexing must handle petabyte-scale data.
  - Real-time indexing not required — periodic batches acceptable.
  - No personalization or user profiling in this phase.
  - Distributed systems complexity — must handle node failures, retries, and horizontal scaling.

Estimating Web Scale

- 🌐 Total indexed pages: ~100+ billion
- 📄 Average page size: ~100 KB
- 💾 Storage required: ~10 PB (raw), ~2–3 PB (compressed)
- 🔍 Daily searches: 5–10 billion (global search engines)
- ⚙️ Target for MVP: 100M pages, 1M QPS capacity, 1PB storage budget

Traffic & Query Load Estimation

- Assumptions:
  - 10M active users
  - 5 queries/user/day = 50M queries/day
  - Peak QPS = ~1000–2000 (with burst handling)
- Query Pattern:
  - 95% read (search queries)
  - 5% write (crawling/indexing updates)

Index Size & Storage Estimation

- Raw HTML content: ~100M pages × 100KB = ~10 TB
- Processed & tokenized content: ~3–5 TB
- Inverted index (terms → doc IDs): ~500–800 GB
- Forward index (doc ID → content): ~5 TB
- Metadata (titles, links, ranks): ~100–200 GB

Crawling Throughput Estimation

- Target: Crawl 100M pages in 7 days
  - Pages/day: ~14.3M
  - Pages/hour: ~600K
  - Pages/sec: ~170
- With 500 crawler workers → ~0.34 pages/sec per worker

🟢 Feasible with politeness & backoff strategies

Query Latency Expectations

- Query parsing: < 5ms
- Index lookup: < 20ms
- Ranking & scoring: < 50ms
- Result formatting: < 10ms
- Total SLA: ⏱️ < 200ms end-to-end

Identifying Key Bottlenecks

- Crawling Layer:
    - Bandwidth limitations & site rate limits
    - Risk of duplicate content
    - ➤ Solution: Distributed crawling, deduplication filters, crawl scheduling, robots.txt adherence
- Indexing Layer:
    - High memory & disk I/O usage when processing large datasets
    - ➤ Solution: Segment-based indexing, compression (e.g., delta encoding, front-coding)
- Query Layer:
    - High QPS can cause latency spikes
    - ➤ Solution: Sharded inverted indexes, result caching (popular queries), fast in-memory lookups
- Storage Layer:
    - Petabyte-scale storage requirement (raw + indexed data)
    - ➤ Solution: Use distributed file systems (e.g., HDFS, S3), columnar formats, cold/hot storage separation
- Freshness Challenge:
    - Web content changes frequently — need efficient re-crawling
    - ➤ Solution: Prioritize high-change-rate sites, adaptive re-crawling intervals, content diffing

Scale-Driven Design Decisions

- Sharded architecture for inverted index
- Use forward & inverted indexes for speed and relevance
- Crawler partitioning by domain hash
- Replication for fault tolerance
- Introduce caching for frequent queries

Core Components of the Search Engine

- 🌐 Web Crawler Service
  - Continuously fetches and downloads web pages from the internet, respecting crawl policies and rate limits.
- 🧭 URL Frontier & Scheduler
  - Manages the queue of URLs to be crawled, prioritizes based on freshness, domain policies, and crawl history.
- 📝 Content Extractor & Parser
  - Cleans HTML, extracts visible text, metadata, and outgoing links for further processing.
- 🧠 Indexer Service
  - Tokenizes, stems, and builds both forward and inverted indexes from parsed content.
- 📦 Document Store
  - Stores raw and parsed versions of crawled web pages along with metadata (titles, crawl date, etc.).
- 📚 Inverted Index Store
  - Maps search terms (tokens) to lists of documents (docIDs) that contain them, enabling fast lookups.
- 🔍 Query Service
  - Parses incoming search queries, looks up inverted index, fetches candidate documents.
- 🏆 Ranking Engine
  - Scores candidate documents using ranking algorithms like TF-IDF, PageRank, and freshness relevance.
- 🛠️ Search API
  - Exposes a user-facing interface (or internal API) to handle search requests and return ranked results.
- ⚡ Cache & Frontend
  - Stores hot query results in-memory (e.g., Redis) and provides the UI or API gateway to users.

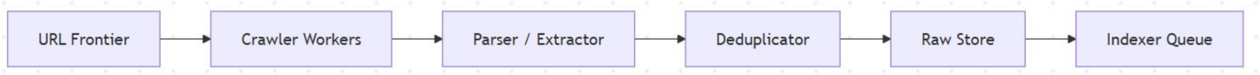
Crawler Coordination Architecture

Crawler Flow:

- URL Frontier: Queue of URLs to visit (distributed, prioritized)
- Crawler Workers:
    a. Fetch pages (respecting robots.txt, rate limits)
    b. Store raw content in Document Store
    c. Push URLs to fetch (links extracted) back to frontier
- Duplicate Detection: Use fingerprints (e.g., SimHash) to avoid re-crawling
- Scheduler: Controls crawl frequency and site politeness

Coordination Strategy:

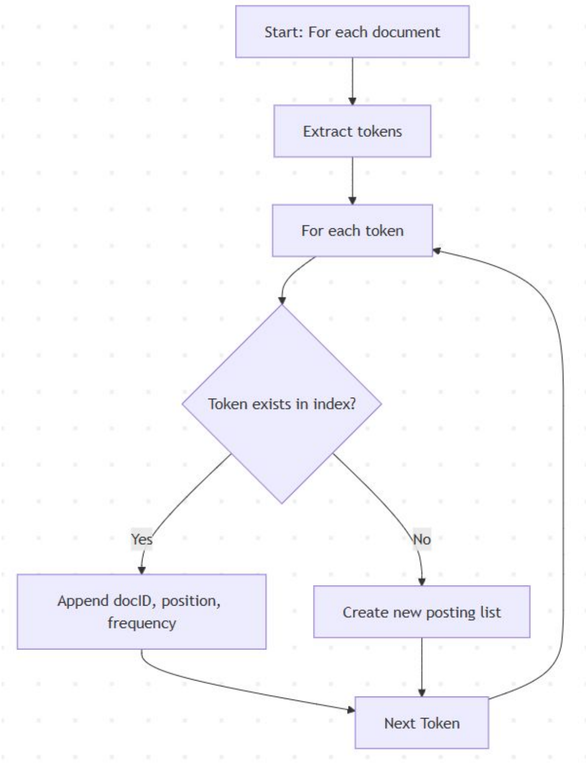
- Distributed workers pulling from sharded queues
- Hash-based partitioning by domain
- Retry & failover handling



Indexing Workflow

- Content Normalization:
  - Strip HTML, tokenize, remove stop words, apply stemming
- Forward Index Generation:
  - Stores docID → tokens + metadata
- Inverted Index Generation:
  - For each token, store list of docIDs with positions, frequencies
- Rank Feature Extraction:
  - Compute PageRank, TF-IDF, and freshness score

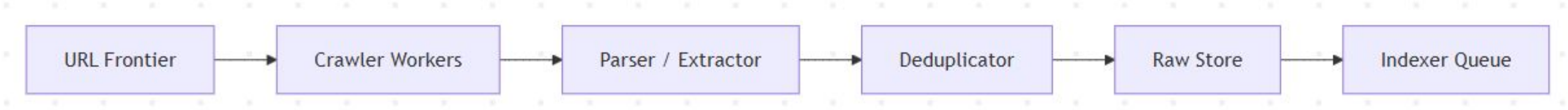
🗃️ Indexes are partitioned and replicated across nodes



Search Query Flow (High-Level)

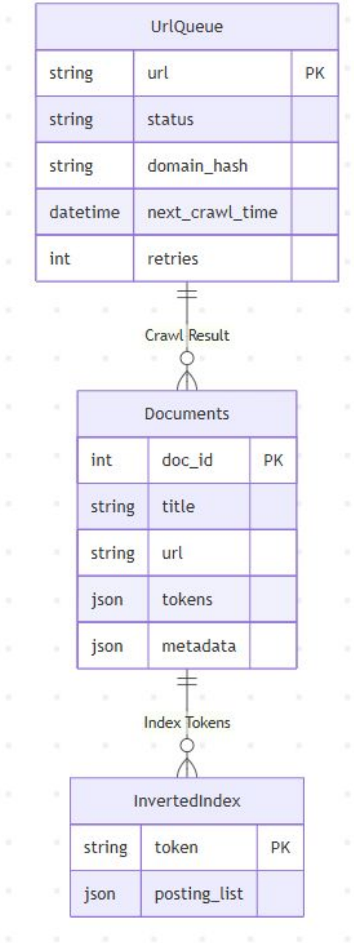
[User Query] → [Search API] → [Query Parser] → [Inverted Index Lookup] → [Ranking Engine] → [Results Returned]

- Results may hit cache (for common queries)
- Top N results formatted with snippet generation



Sample Database Structures

- Crawler DB:
  - Table: UrlQueue
- Search Index DB:
  - Table: Documents (Forward Index Table)
  - Table: InvertedIndex (Inverted Index Table)



Communication Between Components

- Message queues for:
  - Crawler → Parser → Indexer
  - Indexer → Index store
- HTTP/GRPC APIs for:
  - Search API → Query Service
- Caching Layer:
  - Redis or Memcached for hot queries
- Monitoring:
  - Metrics pipeline for crawl status, indexing rate, search latency

Strategic Tech & Infra Decisions

- Crawler Infrastructure:
  - Distributed Crawling: Use a distributed system (e.g., Apache Kafka and Celery) to scale the crawling process and handle large volumes of URLs in parallel.
  - Cloud Providers: Leverage cloud infrastructure (AWS EC2, Google Cloud Compute) for scalability and flexibility.
- Storage Strategy:
  - Relational vs. NoSQL: Use NoSQL (e.g., MongoDB, DynamoDB) for the Documents and InvertedIndex tables for flexible schema and fast lookups.
  - Object Storage for Raw Data: Store raw crawled data and backups in object storage (AWS S3, GCS) for cost-effective and scalable storage.
- Indexing Engine:
  - Custom vs. Pre-built: Build a custom indexing engine or integrate with Elasticsearch for efficient full-text search and ranking.
  - Real-Time Indexing: Ensure the indexing process is continuous, processing documents as they're crawled for near real-time search results.
- Ranking Algorithm:
  - TF-IDF & PageRank: Implement TF-IDF for basic relevance and PageRank for link-based relevance scoring.
  - Freshness Consideration: Introduce freshness ranking to ensure newer content is prioritized in results.
- API & Query Optimization:
  - Load Balancing: Use API Gateways and Load Balancers (AWS ALB, NGINX) to distribute queries evenly.
  - Cache Results: Cache frequently searched queries using Redis or Memcached to improve performance.
- Scalability & Fault Tolerance:
  - Horizontal Scaling: Opt for horizontal scaling (add more servers) to handle growing data and traffic.
  - Failover & Recovery: Implement replication and automatic failover strategies to ensure high availability (using tools like Kafka or AWS RDS).

The Final Design - Search Engine