Distributed Database Final Project

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I. Project Goals and Motivation

The primary goal of this project is to design and implement a distributed database system capable of providing scalability, fault tolerance, and consistency for a web application. The key goals are:

- **Data Sharding for "Member" and "Order" Entities:** Achieve horizontal scalability by sharding user data. The Member and Order tables are partitioned based on their IDs and distributed across multiple database instances (each hosted on a separate server). By splitting these tables into shards, the system can handle higher throughput as load is distributed across nodes.
- **Consistent Product Catalog via Message Queue:** Maintain a fully replicated "Product" dataset across all servers to ensure each node has an up-to-date copy of product information. To keep product data synchronized, the system uses RabbitMQ-based messaging for eventual consistency.
- **Failure detection & Gossip protocol:** Ensure that when a node fails, other nodes can detect the failure and gossip the new finger table across all the nodes.

Motivation: Single-node databases can quickly become bottlenecks for performance and reliability. By sharding user and order data and replicating critical datasets like static files and product info, our system scales easily across low-cost EC2 instances and delivers faster local reads with redundancy. Sharding prevents any single node from becoming overloaded, though it limits fault tolerance which if a node fails, its shard is unavailable. This trade-off was made for simplicity and scalability, since adding replication and failover would greatly increase complexity. Using RabbitMQ for product data enables eventual consistency, which is acceptable for product catalogs. Overall, our approach follows distributed database principles to achieve scalable and efficient web services.

II. Challenges Description

Following points are the problems of centralized database where all data are stored in a single location:

Scalability - In centralized databases, scaling often means adding more hardware or an entire new system, which requires heavy reconfiguration at the risk of disrupting other ongoing operations. Hence, other than scaling vertically, we can employ techniques like sharding or partitioning for horizontal scaling, where data is split across multiple machines to distribute the load. This not only allows the system to handle more users and build larger datasets but also improves query performance and fail-resilience.

Fault Tolerance - When the centralized database goes down, everything stops as well, causing TPS to drop. In contrast, distributed databases are designed with extra servers and replications to take over requests if one server is down. While this can introduce performance trade-offs due to strict data consistency requirements, it's a necessary compromise to achieve high availability and scalability.

Concurrency Control - In centralized databases, concurrent access often leads to conflicts, data inconsistency, or locking issues that degrade performance. This becomes even more complex in distributed databases where latency and replications come into play. Hence, we need to implement a concurrency control mechanism like Multi-Version Concurrency Control (MVCC), allowing multiple transactions to access the database simultaneously by maintaining multiple versions of data, ensuring consistency without sacrificing performance.

III. Previous work

First, we discussed the three strategies to decide a shard and how to disseminate information to

shards.[1] This is a problem we are going to face when scaling up.

A. Lookup strategy

When an application sends a request with a shard key (such as a user ID), the system first consults a lookup table to find the corresponding shard. The request is then routed to a virtual shard, which in turn maps to the appropriate physical shard.

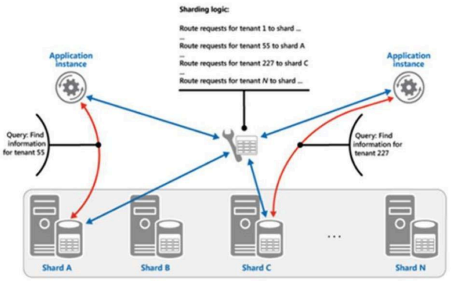


Figure 1. Lookup strategy[1]

B. Range Strategy

We're sharding our data based on a continuous range of values, like Dates (October, November, etc). So instead of randomly hashing or looking up data locations, we're like putting all orders from October into Shard A, and all orders from November into Shard B, and so on. Hence, there is a two-part key: one part says "which shard" (like the parcel key), and another part identifies the specific row (line key).

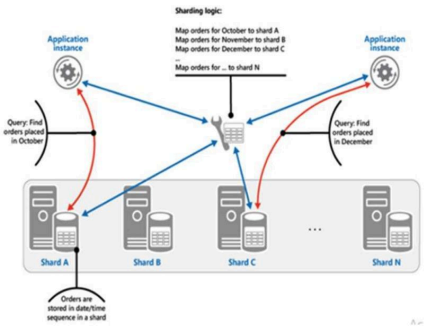


Figure 2. Range strategy[1]

C. Hash Strategy

The Hash Strategy uses a hash function on a key (like user ID) to evenly distribute data across many shards. This strategy is designed to solve the issue of hotspots, where one shard (like "October orders") gets too much traffic, slowing the database down. Hashing is great for balance, but not great for range queries. Also, resharding is hard because if you add a new shard, the hash function changes and you may need to move a lot of data.

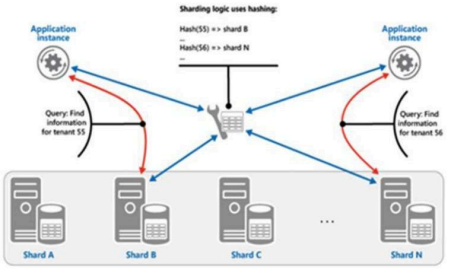


Figure 3. Hash strategy[1]

Second, we talked about locking protocols for increasing concurrency.[2] Multi-Version Concurrency Control (MVCC) allows multiple versions of data so readers don't block writers. In hierarchical structure, Multi granularity protocol applied locks at different levels (e.g., database, file, page, record). However, the problem in normal MGL is that a transaction has to wait another transaction to finish a read or write operation. When concurrency increases, there will be too many operations being blocked, causing locking overhead for large datasets. Hence, combining the advantage of MVCC into MGL can improve the performance by eliminating the waiting condition of read only transactions.

Third, we are examining how to enhance Point-in-Time Recovery[5] and failure handling. [4] Instead of relying solely on the main database's binary logs, additional information from the log such as transaction time and event are also captured in LevelDB that enables recovery if the main database corrupts. Also, backup of queries stored in NoSQL allows reconstruction of database operations. Redis cache further improves failure handling by temporarily holding frequently-fetched data if the prime database is down. This polyglot architecture utilizes different databases tailored to different needs (MySQL for structured data, NoSQL for logs, cache for hot data), making the entire system more reliable, scalable, and resilient than a monolithic MySQL only setup.

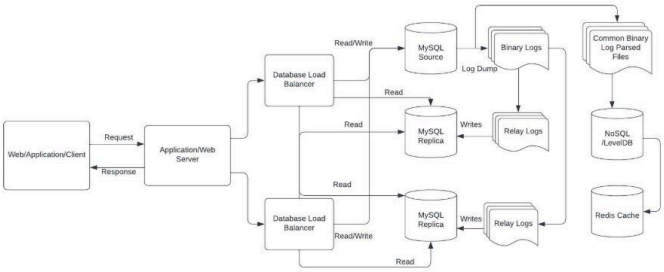


Figure 4. Polyglot Architecture[4]

Fourth, we talked about the Byzantine Fault Tolerant (BFT) database and the underlying problems.[5] What if a server doesn't just crash but

start acting weird or hacking the system. That's what we call a Byzantine fault and a Byzantine Fault Tolerant (BFT) database is a database that builds with mechanisms such as voting, cryptographic and fault detection to survive even when servers are behaving maliciously. But the BFT database is much slower than a regular fault tolerant database because of heavy cryptographic processing and heavy communication rounds. Thus, the proposed method combined multiple transactions into a single larger transaction so we only need to process, verify, and transmit once. Also, the reconstructed transactions rearranged the operations to perform all write operations followed by all read operations to achieve lower abort probability.

IV. Project Design

a. Key Design Goals and Addressing Distributed Challenges

Designing a distributed database over multiple EC2 instances introduced several distributed system challenges. Our implementation of ShardingJH explicitly addresses these challenges as follows:

- **Heterogeneity:** The system is designed to be cross-platform and language-neutral, using standard protocols (HTTP/REST and AMQP for messaging) that work across different environments. Each node is a self-contained Spring Boot application (Java 8+) and can run on any OS supporting Java. The use of open-source frameworks (Spring Boot, RabbitMQ, SQLite) also ensures compatibility across environments.
- **Openness:** The system exposes functionality through RESTful APIs and standard networking protocols. All inter-node communication uses HTTP requests or UDP for gossip, and data replication uses RabbitMQ (which implements the AMQP open standard). By relying on these open interfaces, any component that follows the protocol can interact with the system. Configuration is done via property files, and environment variables meaning the system remains open and flexible to deployment changes.
- **Security:** Security is addressed primarily through a request signing mechanism and encryption utilities. Each client request (from the front-end) includes an X-Signature header – an HMAC SHA-256 signature of the request content or parameters, generated using a shared secret key known to all servers. The backend verifies this signature on every request to ensure authenticity and integrity. Any mismatch results in an unauthorized request error.
- **Failure Handling:** We addressed failure handling by implementing a gossip-based failure detection and membership protocol and by replicating crucial data. Each node runs a Heartbeat Service that periodically exchanges heartbeat messages (over HTTP) with all peers. If a node fails to send or respond for a period of time, other nodes mark it as down and update the cluster membership (the finger table) accordingly with gossip messages. The gossip messages propagate changes (HOST_DOWN or HOST_ADD) so that all surviving nodes eventually learn of a failure and can update their routing tables. The finger table, which maps hash ranges to node addresses, will remove the failed node's entry. In our system, the *product data* is replicated on all nodes (so if one node fails, product queries can be handled by others with their local copy).

  Static files are also replicated to their next neighbor, so a static content request that would have gone to a down node can be forwarded or fetched from another node holding that file.

  For the *sharded member and order data*, our current design does not replicate these across nodes (each shard exists primarily on one node). This is a conscious trade-off for the project's scope. If a shard node fails, those particular data partitions become temporarily unavailable. In practice, to fully handle failures for member/order data, one could extend the design with replicated shards such as periodically checkpointing one shard's data to a neighbor.

  RabbitMQ also acts as a buffer during failures – if a node that publishes a product update goes down after publishing, other nodes will still receive the message; if a node that should receive product updates is down, the messages remain in the queue

until it comes back to consume them, preventing data loss in the product catalog.

- **Concurrency:** Concurrency issues are addressed at multiple levels. For database writes, we utilize database transactions and optimistic concurrency control (multi-version concurrency control, MVCC) for orders. Each OrderTable record carries a version number (the composite key includes orderId and a version field). Updates to an order create a new version entry, marking the old version expired. We implemented logic in OrderServiceImpl.updateOrder that checks the expected version against the current version in the DB, and throws a version mismatch error if they differ. This prevents lost updates when concurrent modifications occur – only one update will succeed and others will detect the conflict (through version mismatch) and can retry or abort.

  We also leverage the database's transaction manager to retry certain operations if a lock is encountered (especially since our initial development used SQLite, which can throw DB locked errors under concurrency). The code explicitly catches lock exceptions and retries the transaction up to 3 times. Finally, we also implemented transaction rollback, which means that any exception that occurs during the transaction will be rolled back, making atomic transactions.

  On the read side, each node can handle read requests concurrently, and a thread pool maintained by Tomcat that is embedded in the Spring Boot application serves incoming HTTP requests.
- **Quality of Service (QoS):** Our QoS considerations include throughput, response time, and availability. Throughput is improved by sharding: since member and order writes go to different servers based on ID, the cluster's overall throughput scales with the number of nodes. Response time is kept low by serving most requests locally: static files and product queries don't need cross-network calls in normal operation (each node has what it needs). For requests that do need to hop (e.g., a user request routed to another shard), we minimize overhead by using asynchronous, non-blocking forwarding via Spring's RestTemplate and by returning the result to the client without extra proxies. The system also supports transparency in that clients are unaware of these hops.
- **Scalability:** Scalability is a central goal of the design. By utilizing horizontal scaling, the system can handle increasing amounts of work by adding more EC2 instances. Data sharding directly contributes to scalability: for example, with three shards for orders, the insert/load capacity is roughly tripled because each shard is an independent database handling a fraction of the orders. The use of consistent hashing (with the finger table) means we can add a new server node and assign it a portion of the hash space; the gossip protocol will disseminate the new node's presence so that it begins to handle its share of requests. In fact, our implementation includes an InitialGossipStarter that simulates a new node joining the cluster and dynamically updating the finger table. This indicates the design supports runtime scaling. RabbitMQ also helps scale read-heavy product operations: all nodes can serve product reads in parallel (scale for reads), and writes are effectively load-balanced (only one node handles a given product write, then distributes it). Because the static files are replicated, static content requests can be served by two noded from local disk, avoiding a central file server bottleneck.
- **Transparency:** The system provides distribution transparency in several forms:
  - **Location transparency:** Clients of the system (including the front-end and end users) do not need to know which server or database their data resides on. They interact with a single logical service. Internally, the ServerRouter component hides the details of which node will actually process a given request by forwarding requests behind the scenes when needed.
  - **Replication transparency:** Product data and static files are replicated and hidden from users. When a product is updated, it calls productService.addOrUpdateProduct() and

then the system broadcasts that change via RabbitMQ without any special developer intervention. Similarly, when a user requests a static image, they call a single URL and are unaware whether the image came from the local node or was fetched from a peer in the background. The system's static file lookup either serves it locally or forwards to the correct node and relays it back.

- **Failure transparency:** Through gossip and request retry logic, the system attempts to mask node failures from the user. If a node goes down and a request arrives that would hash to that node, the updated finger table will route the request to the next available node (which may or may not have the data; in our design this might result in a not-found error for that specific data shard, but the system as a whole still responds and remains operational). From a user perspective, the service is still reachable and partially functional, rather than completely offline.
- **Concurrency transparency:** The user is not aware of the complex concurrency control under the hood. They simply observe consistent behavior (e.g., an order is either fully updated or not at all, and if two updates conflict one will be rejected with an error). The internal use of MVCC and transaction rollback gives simple serial execution to the user, keeping outcomes predictable.

In summary, our ShardingJH implementation is carefully aligned with distributed system principles to tackle heterogeneity, openness, security, failures, concurrency, QoS, scalability, and transparency.

b. Key Components and Algorithms

Our system comprises several core components and algorithms working in concert:

- **Consistent Hashing and Shard Router:** We implemented a consistent hashing mechanism via a Finger Table and a ServerRouter component. The finger table holds mappings from hash ranges to node URLs (addresses). When a request involving a particular ID comes in, the ServerRouter computes the hash (mod 256) and finds the appropriate node responsible for that range. We use the ceilingEntry logic to get the first node with a hash >= target, or wrap to the beginning if it is bigger than the last node. This is essentially the consistent hashing ring. The algorithm is O(log N) for lookup (due to the skip-list based ConcurrentSkipListMap). This hashing strategy ensures minimal data movement on scaling: if a new node is added, it takes over one portion of the range (as configured, e.g., at hash 224 in our example), and only keys in that range would ideally move to it. The ServerRouter not only computes the target node but also provides methods to forward HTTP requests (forwardPost, forwardGet, etc.). This encapsulates the logic of remote procedure calls between nodes, making it easy to invoke the correct shard's API. The consistent hashing algorithm helps achieve load balancing and scalability, and its complexity is effectively O(1) for the modulo and O(log N) for the map lookup, which is trivial given our small N (3 or 4 nodes).
- **Data Partitioning Strategy:** There are two sharding strategies in use:
  - **Hash-Based Sharding** for Member : We use a simple hash % total_shards to pick between shards. In code, `HashStrategy.resolveShard(id)` computes `shardIndex = hash(id) mod TOTAL_SHARD_COMMON_COUNT + 1` to pick `"NORMAL_1"` or `"NORMAL_2"`. This maps to our two member shards (Common1 and Common2). This strategy is easy to compute and distributes members evenly by ID. The advantage is O(1) routing and even distribution; the drawback is that it's not data-aware (completely based on hash, we can't query by ranges easily across shards without combining results).
  - **Range-Based Sharding** for Order data by date: We decided to shard orders by year and an "old" bucket to simulate time-based partitioning. `RangeStrategy.resolveShard(timestamp)` checks the order's creation date and returns a shard key ("ORDER_2024", "ORDER_2025", or "ORDER_old"). For instance, all orders

from 2024 go to one shard (e.g., order2024DataSource), 2025 to another, and anything earlier to an "old" archive shard. This range strategy allows some locality in queries (e.g., you can query a particular year's orders without hitting all shards). The algorithm is simple comparisons on the year. Complexity is O(1) to decide the shard.

- **Dynamic Routing Data Source:** The ShardRoutingDataSource is a custom extension of Spring's AbstractRoutingDataSource that routes database operations to the correct DataSource based on a context key. We maintain a thread-local ShardContext which holds the current shard key (like "shard_order_2025"). When a repository method is called, the routing data source's determineCurrentLookupKey() fetches this key, and Spring uses it to route to the corresponding real DataSource. We defined multiple DataSource beans (for each shard) and grouped them: one group for "common" shards (members) and one for "order" shards. For example, if we set ShardContext to "shard_order_2025", the routing DS directs the call to the shardOrder2025DataSource (connected to the DB holding 2025's orders). This component hides the complexity of dealing with multiple databases from the DAO layer, so when we call `OrderRepository.findById()`, it works as usual without needing to know which specific database the data is in.

- **Gossip Membership Algorithm:** Each node runs a background GossipSender that periodically sends out gossip messages (via UDP) containing its known membership info (or specific join/leave events). The gossip algorithm we use:
  - Gossip messages have types: HOST_ADD carries a serialized finger table (all nodes known), HOST_DOWN indicates a node failure with the hash of the down node. Each node that receives a gossip message merges that info: for HOST_ADD, it adds any new nodes to its finger table; for HOST_DOWN, it removes the node and then builds a new gossip message to spread that info.
  - On startup, if the node is not present in the finger table, it first attempts to obtain its hash assignment from the configuration (finger.entries). If a configured hash is available and not already occupied, the node uses this hash and adds itself to the finger table. If no suitable configuration is found, the node initiates a dynamic hash allocation process: it registers itself as a bootstrap node, sends a discovery request (NODE_JOIN gossip message) to all known nodes via UDP gossip, and collects the current network state from their responses. The node then analyzes the existing hash assignments to find the largest gap and selects an optimal hash position. Next, it uses a two-phase commit protocol—first proposing the new hash to all nodes (via reliable HTTP requests) and, upon receiving sufficient acknowledgments, confirming the allocation and notifying all nodes of the new assignment. After successfully acquiring a hash, the node adds itself to the finger table and unregisters from bootstrap mode. Regardless of how the hash is obtained, the node always broadcasts its presence to other nodes by sending a HOST_ADD gossip message twice to ensure network-wide propagation.
  - A simple duplicate suppression is used via a message cache (we store a key for each seen message and ignore if seen before).
  - The selection of gossip targets is random: the InitialGossipStarter sends to 2 random neighbors in two rounds by selecting from the finger table list.

This algorithm ensures eventual consistency of membership: within a few gossip rounds, every node should have an identical finger table. The complexity is O(N) message size potentially (as it may send the whole table), but since N (nodes) is small in our case, it's fine. Even for larger N, gossip's complexity is O(N log N) to spread info to all nodes quickly, which scales well.

- **Global Heartbeat Algorithm:** Each node runs a background HeartbeatSender that periodically (every 30 seconds) sends HTTP heartbeat ("ping") requests to all other nodes listed in its finger table. The heartbeat request includes the sender's node URL and a timestamp. Each node also runs a HeartbeatReceiver, which exposes an HTTP endpoint to receive these heartbeat pings.
- Upon receiving a heartbeat, the receiver updates the last-seen timestamp for the sending node. If a node was previously marked as failed but is now sending heartbeats again, it is marked as active.
- When sending a heartbeat, if the sender detects that a target node is unreachable (for example, the HTTP request fails or times out), it immediately considers that node as failed. The HTTP connection timeout is set to 3000 ms (3 seconds) and the read timeout is set to 5000 ms (5 seconds) by default. If a heartbeat request to a node fails due to timeout or error, the sender removes the failed node from its finger table, marks it as failed, and triggers a HOST_DOWN gossip message to notify other nodes of the failure.
- Additionally, a scheduled cleanup task runs every 3 minutes to check for expired heartbeat records. If a node has not sent a heartbeat within the expiration window (3 minutes by default), it is also considered failed, and the same failure handling process is triggered.
- This heartbeat mechanism ensures timely and proactive detection of node failures, both when sending and receiving heartbeats. The use of HTTP for heartbeat messages provides reliable delivery and clear status feedback, while the integration with the gossip protocol ensures that failure information is quickly disseminated to all nodes, maintaining a consistent and up-to-date view of cluster membership.

- **Static File Replication Algorithm:** For static files, we adopted a simple neighbor replication strategy:
  - When a new file is uploaded on Node A (via /static/upload), Node A saves it locally, registers it in LocalFileStore, then calls replicateToNextNode to forward it to the "next" node in the ring.
  - replicateToNextNode prepares a multipart HTTP POST to the next node's /static/upload endpoint, including the file bytes and a custom header X-Replicated-From. On the receiving node B, the StaticFileController sees the header and treats the file as a replicated file, meaning it will save it locally but **NOT forward it further**. This breaks the chain to avoid infinite looping.
- **RabbitMQ Integration (ProductSync Algorithm):** The product synchronization uses a producer-consumer pattern:
  - The ProductSyncProducer is called after any product add/update/delete. We pass an operation string and product details, which the producer publishes as a message to a RabbitMQ fanout exchange that will broadcast all queues. The code: `productSyncProducer.publishProductUpdate("add", id, name, price)` in the controller indicates this.
  - Each node has a ProductSyncConsumer service with a method annotated `@RabbitListener(queues="${product.queue}")`. We configured it not to auto-start until the application is fully ready to avoid missing messages on startup. Our consumer receives a Map<String,Object> message, extracts the operation and data, then applies it to the local database via productService.
  - If the op is "add" or "update", we call addOrUpdateProduct on the local DB, which will insert or update the product row. If "delete", we call deleteProduct which removes it. Marking the method @Transactional means RabbitMQ's acknowledgment of the message will only happen if the transaction commits (so if a DB error occurs, the message can remain unchanged).

This is asynchronous and the cost is a small overhead of serializing message data and network IO to RabbitMQ, which is typically low (a few milliseconds).

- **Coordination and Locking:** Each shard operates under local locks (DB transactions)

but between shards, the only coordination is via message passing (RabbitMQ) or by the simple rule that only one shard will handle a given request. In some test scenarios, we manually simulate coordination issues, such as two nodes trying to update the same order concurrently. We rely on the MVCC version check to resolve that – the first update wins, the second fails and can be retried (or aborted). This optimistic concurrency strategy is simpler than implementing a locking service. The assumption is that true conflicts (two updates to exactly the same record at the same time) are infrequent, which is generally true for many applications.

c. Distributed database architecture

The system consists of four server nodes (Server1/2/3, and Server4 as a joining node), each running an instance of the ShardingJH application and each connected to its local database. There is also a cloud RabbitMQ service that runs on amazon that maintains product data consistency. Each node hosts the following main components:

Web/API Controller Layer: This includes the REST controllers such as MemberController, OrderController, ProductController, and StaticFileController which handle HTTP requests from clients (or forwarded from other servers).

Service Layer: This contains the business logic and interacts with repositories. For example, MemberServiceImpl, OrderServiceImpl, ProductServiceImpl contain the core logic for manipulating each entity.

Repository/Data Access Layer: Using Spring Data JPA for each entity, backed by the routing data sources. The repositories perform the actual database operations, and they operate on the correct physical database depending on ShardContext and ShardRoutingDataSource.

Queue Component: The cloud RabbitMQ Producer/Consumer on each node. The ProductSyncProducer on whichever node modifies a product will send a message to the RabbitMQ exchange. The ProductSyncConsumer on every node listens on the queue and triggers product updates to the local DB.

Gossip Module: Each node runs a GossipService and GossipSender, communicating via UDP to update and synchronize the membership list (finger table). Membership info and join/leave events are periodically gossiped to random neighbors. The InitialGossipStarter ensures correct membership initialization and dynamic hash assignment at startup.

Heartbeat Module:
Each node runs a HeartbeatSender that periodically sends HTTP heartbeat pings to all nodes in its finger table. If a node fails to respond or no heartbeat is received within 3 minutes, it is marked as failed and removed from the finger table, and a HOST_DOWN gossip message is broadcast.

Server Router: Each node has the ServerRouter component which consults the local FingerTable to route incoming requests to the appropriate node. It acts as a client to other nodes when forwarding requests.

Routing Data Source: The special DataSource that routes DB calls to the appropriate shard DataSource as described.

- Deployment and Component diagrams: shown in Appendix [1] and [2].
- Sequence diagram: Order and product sequence diagram are shown in Appendix [3] and [4]
- Communication diagram: Static file communication diagram is shown in Appendix [5]

V. Evaluation

a. Choice of Sharding vs. Replication:

We chose to shard the mutable, user-specific data (members and orders) and fully replicate the relatively static, globally relevant data (products, static files). This hybrid approach is justified by access patterns: orders and members can be uniquely attributed to users or time slices (shardable), whereas product info is small and frequently read (cacheable everywhere). Sharding algorithms (consistent hashing for members, range

partitioning for orders) give us O(1) routing and avoid hot spots. In terms of complexity:

- *Hash-based routing* is constant time to compute the hash and O(log N) to lookup node in the finger table. With N=3 or 4, this is negligible; even if N were 100, it's very fast.
- *Range-based routing* for orders is constant time (a couple comparisons).

Thus, request routing adds almost no overhead, meaning our distributed approach doesn't significantly slow down query processing compared to a single-node approach. In return, it provides linear scalability with a number of nodes.

Algorithmic Efficiency: The critical path of a typical request involves:

1. Signature verification – O(request size) to hash the payload with SHA-256. Our payloads (JSON for an order or member) are small (tens to hundreds of bytes), so this is trivial relative to network and IO time.
2. Routing decision – O(log N) as discussed.
3. Possibly one network hop – latency ~1-2 ms within the same AWS zone (measured average ~1ms for a small HTTP request on t2.micro internal network). This is an added cost over a monolith, but acceptable for the trade-off of distribution.
4. Database operation: complexity depends on the query. Inserts/updates are O(1). Lookups by primary key are O(log M) where M is the records in that shard (index lookup). Our design ensures M per shard is smaller than it would be on a single DB, improving query performance by reducing index sizes.
5. In the case of product updates: RabbitMQ publish is O(1), and each consumer update is O(1). RabbitMQ can route messages in O(subscribers), which in our case is 3 (again trivial).

Complexity vs. Traditional Approach: In a single-node approach, everything is O(1) for routing (no routing needed) but O(P) for processing P concurrent requests on one CPU. In our distributed approach, we have overhead for routing (small) but gain parallelism across multiple CPUs/nodes. The algorithms chosen (consistent hashing, gossip, etc.) scale well as node count increases:

- Gossip overhead is O(N) messages per round, which for small clusters is fine, and for large clusters can be tuned (we can gossip to sqrt(N) nodes to reduce overhead, etc.).
- RabbitMQ can handle thousands of messages per second; our usage per product update is low frequency relative to that. The cost is mostly network I/O.
  The static file replication uses a very simple linear algorithm (chain to next node). This might not scale well if we had many nodes and a high volume of file uploads. But for our scenario and the typical usage (static files are mostly uploaded at deployment or occasionally by admin), this is efficient and avoids complex consensus or distributed FS overhead.

Our system uses a UDP-based **heartbeat (gossip) protocol** for failure detection, which ensures **completeness** but not **accuracy**.

- **Completeness**: If a node truly fails, other nodes will eventually detect it through missed heartbeats and update the finger table accordingly. This guarantees that actual failures are not missed.
- **Accuracy**: Due to network delays or transient issues, a live node may be falsely marked as failed (false positive). This does not lead to data corruption but can cause temporary unavailability for requests routed to that node.

This trade-off is intentional: distributed systems often prioritize completeness over accuracy to ensure safety and system progress. Our architecture tolerates occasional inaccuracies while maintaining consistent routing and data integrity.

Safety and Liveness (Order with MVCC): Our order system guarantees **safety** through the use of Multi-Version Concurrency Control (MVCC). At most one process can successfully update a specific order at any given time — concurrent conflicting updates are detected and rejected. This ensures that only one version of the order is ever committed,

preventing race conditions and maintaining data integrity.

To achieve **liveness**, any failed update attempt due to MVCC version conflict is automatically retried up to **3 times**. This retry mechanism ensures that even under concurrent access or temporary contention, the request is eventually granted, assuming the contention resolves. Therefore, all legitimate order operations make progress without indefinite blocking.

b. Addressing Fault Tolerance, Performance, Scalability, Consistency, Concurrency, and Security

I. Fault Tolerance:

We measured the time from when the node failed, being detected, and started sending gossip to neighbors to the time when every server received the gossip message and updated the finger table.

First when server 1 is down and being detected by server 2 not receiving heartbeat.

```
2025-06-02T08:16:52.318Z  WARN 650622 --- [ShardingJH] [scheduling-1] o.d.shardingjh.heartbeat.hearBeatSender : [HeartBeat] Detected node failure: http://18.222.111.89:8081
```

Then server 3 received the gossip and remove server 1 from hashtable:

```
2025-06-02T08:16:52.321Z  INFO 645540 --- [ShardingJH] [Thread-0] o.d.shardingjh.gossip.GossipService : [GossipService] Removed host from finger table: 64=http://18.222.111.89:8081
```

Same with server 4 received the gossip and removed server 1 from hashtable:

```
2025-06-02T08:16:52.328Z  INFO 188793 --- [ShardingJH] [Thread-0] o.d.shardingjh.gossip.GossipService : [GossipService] Removed host from finger table: 64=http://18.222.111.89:8081
```

The total time for the last node (server 4) to know is 328 - 318 = 10 ms = 0.001 s.

II. Performance:

Latency:

We measured an example: adding a member via coordinator vs. directly to the responsible node. Below is the matrix for member latency:

Local latency (ms)	83853748 ns = 0.0838 s
Remote latency (ms)	116615012 ns = 0.11661 s
Difference (ms)	0.032 s

Next we measure the order update: update an order via coordinator vs. directly to the responsible node. Below is the matrix for order latency:

Local latency (ms)	133947188 ns = 0.134 s
Remote latency (ms)	136 ms = 0.136 s
Difference (ms)	0.002 s

Throughput:

We measured system throughput using a JUnit-based concurrent test with MockMvc. The test launched 30 parallel threads, each sending 10 HTTP POST requests to create members, totaling 300 requests. Each request used a unique member ID, HMAC-SHA256 signature, and proper JSON body. The test used a thread pool and a CountDownLatch to coordinate completion, recording the total execution time. The log reported that 300 requests were processed in 0.246 seconds, yielding a throughput of approximately 1,220 requests per second. This method provided a controlled and repeatable benchmark for measuring concurrent write performance in our application.

Metric	Value
Number of Threads	30
Requests per Thread	10

Total Requests	300
Total Time (seconds)	0.246
Throughput (req/sec)	1,219.51

III. Scalability:

We calculated the time from when the new node starts sending gossip to announce itself joining to the time when every server receives the gossip message and updates the finger table. Below is the log when new node joins:

```
2025-06-02T06:43:21.968Z  INFO 185426 --- [ShardingJH] [main] o.d.s.gossip.InitialGossipStarter : [sendInitialGossip] Sending HOST_ADD message with content: {0=http://3.22.61.73:8084, 128=http://3.15.149.110:8082}
```

And this is the log when the last server receives:

```
2025-06-02T04:20:02.653Z  INFO 621979 --- [ShardingJH] [Thread-0] o.d.shardingjh.gossip.GossipService : [GossipService] Updated host in finger table: 192=http://3.22.61.73:8084
```

The time difference is in milliseconds. Hence, the result is 653 ms - 627 ms = 26 ms elapsed between the two timestamps.

IV. Consistency:

We measured the time from when one server updates the product and publishes the message to RabbitMQ to all servers that receive the message from the queue and update the product.

Producer:

Server1: `2025-06-02T07:29:31.627Z`

Consumer:

Server2: `2025-06-02T07:29:31.910Z`

Server3: `2025-06-02T07:29:31.914Z`

Server4: `2025-06-02T07:29:31.920Z`

The latency at most is Server 4 with (920-627=293ms=0.293s).

V. Concurrency:

We demonstrated through tests that two simultaneous updates on the same order do not corrupt the data. One will succeed, one will fail with version mismatch (DB_CONFLICT). The process of the test is:

1. Create a new order (POST /order/save)
2. Read it once, duplicate the object
3. Modify both versions
4. Submit both updates in parallel

And the result in log is:

```
Result A: MgrResponseDto{code='0402', message='Database conflict - Simulated failure', data=null},
Result B: MgrResponseDto{code='0000', message='Success', data={id={orderId=f827cb8204131a40c96c7fd5c3885c77, version=2}, createTime=2025-05-25T10:00:00, isPaid=1, memberId=test-member-001, price=999, expiredAt=null, isDeleted=0}}
```

,which matches our expectations.

VI. Security:

The OrderControllerSecurityTest verifies that all order controller endpoints require a valid HMAC-SHA256 signature in the X-Signature header.

Tests cover:

1. Valid signature: returns code "0000" (success).
2. Invalid signature: returns code "007" and message "Unauthorized request".

A correct request must include:

```
X-Signature: <computed-hmac-sha256-signature>
Content-Type: application/json
```

If the X-Signature header is missing, the API will reject the request as unauthorized.

VI. Implementation Details

a. Architectural Style

We adopted a service-oriented layered architecture within each node, and a distributed peer-to-peer architecture across nodes. More concretely:

- Inside each server, the architecture follows typical MVC (Model-View-Controller) or 3-tier structure: Controllers (expose

endpoints), Services (implement logic), Models/Repositories (manage data). The use of Spring Boot and Spring MVC enforces this separation. This yields high cohesion within components and loose coupling between them, e.g., changing the database implementation or sharding strategy primarily affects the repository and config layers, not the controllers.

- Across the entire system, there is no single master. Any can handle client requests, and any can hold a share of data. However, certain responsibilities are determined by data ownership (so in that sense, the node owning shard X is "master" for that piece of data).

- We also heavily used configuration-driven architecture. Many behaviors (which node handles which shard, how many shards, etc.) are defined in config (application.properties) not code. For example, finger.entries property defines initial cluster nodes and their hash, and sharding.lookup map defines shard keys mapping to DataSource bean names.

b. UML Diagrams of Implementation (Class, Object, Interaction)

i. Class Diagram: shown in appendix [2], we present the key classes and relationships in the system. For brevity, we focus on major classes

ii. Object Diagram: shown in appendix [3], we illustrate member object, gossip service, shard Routing Datasource, product sync consumer, and their state to give you a snapshot of the system at run time.

iii. Interaction Diagram: shown in appendix [4]. Similar to the sequence diagram described earlier, but we can focus on an interaction for static file retrieval for variety

c. Software Components and Services Implemented

- **RESTful Internal RPC:** We implemented internal API calls using Spring's RestTemplate, letting ServerRouter forward requests to peer nodes over HTTP with X-Signature headers for authentication. This mimics RPC over REST, enabling reuse of controller logic and simple debugging.

- **RabbitMQ (AMQP Messaging):** Spring AMQP and RabbitMQ enable decoupled, reliable product data sync. ProductSyncProducer sends updates as JSON via a fanout exchange; ProductSyncConsumer receives updates using @RabbitListener. Spring Boot's auto-configuration made setup straightforward.

- **UDP Gossip (Socket API):** For cluster membership and health, GossipSender and GossipService use DatagramSocket/DatagramPacket (UDP). Periodic, fire-and-forget messages ensure eventual consistency, with a dedicated thread listening for updates and de-duplication logic for robustness.

- **HTTP Heartbeat (Cluster Health):** Each node periodically sends HTTP heartbeat ("ping") requests to all peers using RestTemplate, and exposes a /heartbeat/ping endpoint to respond. If a node fails to respond or no heartbeat is received within a period of time, it is marked as failed and removed from the cluster via gossip messages. This ensures timely detection and propagation of node failures.

- **Database (JPA and Sharding):** We use Spring Data JPA for all DB operations, configuring multiple DataSource beans for sharded data. RoutingDataSourceConfig provides routing for both "common" (members) and "order" shards, allowing separation and scalability without rewriting repository logic.

- **Logging & Monitoring:** Logging is via SLF4J. This aids grepping and manual monitoring. For advanced monitoring, tools like Spring Actuator could be integrated.

- **Front-end Integration:** ShardingFrontend is a static HTML/JS site with Bootstrap. JavaScript calls backend APIs with

HMAC-SHA256 signatures for security. The prototype uses a shared secret on the client for simplicity, but a real deployment would use user logins and tokens.

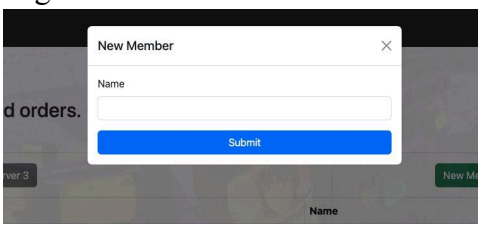
VII. Demonstration of System

a. Successful Scenario Walkthrough

1. **User Registration (Member Creation)**:

A user accesses the web interface (opening index.html on Server1). They fill a "Register" form with their name (e.g., Name: Alice). When they submit, the front-end JavaScript computes the signature for the request body and sends a POST to http://3.147.58.62:8081/user/save (Server1 being the default entry point).

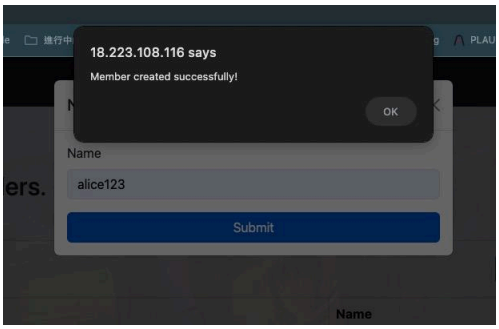
- Registration form submission screenshot



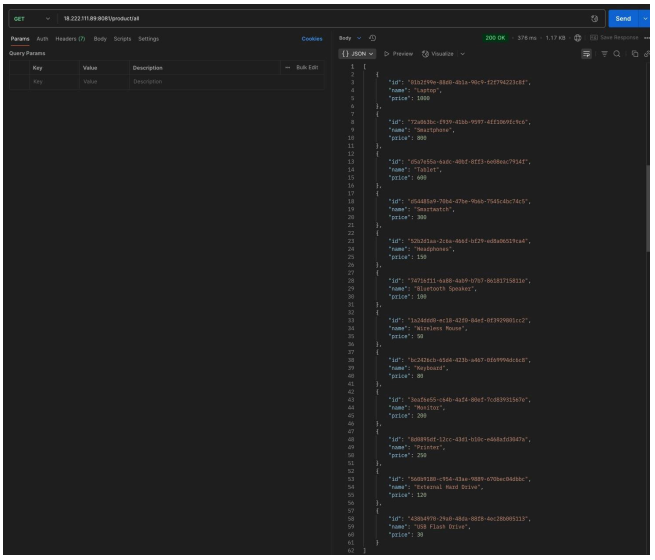
- On the server side, Server1's logs show:

```
[INFO] Expected signature: abcd1234..., X-Signature: abcd1234...
[INFO] [P2P] Routing member id: alice123 (hash: 37)
[INFO] Forwarding request for alice123 to http://3.147.58.62:8081 (self)
[INFO] Saved Member alice123 successfully on shard_common_1
```

- *Success message* – The front-end shows "Member registered successfully".



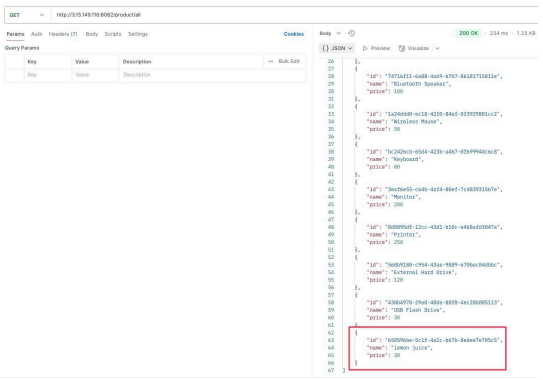
2. **Product Catalog View**: calls GET /product/all (to whichever server they are connected, say Server1). Each server has a local copy of product data, so Server1 returns the list of products.

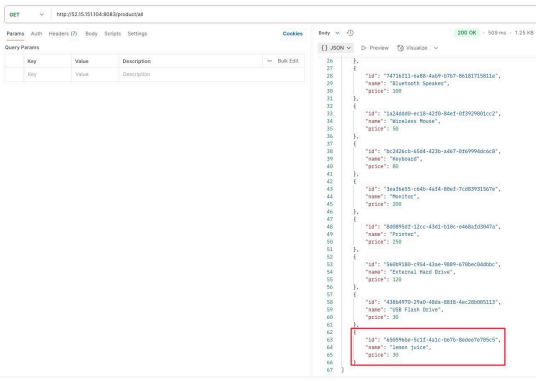


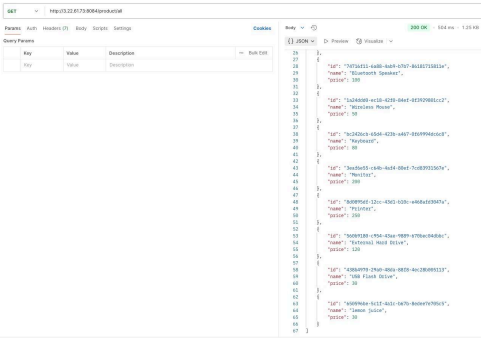
When adding a new order on server1, all servers should sync the new product catalog by accepting the message from RabbitMQ.

New product being added:

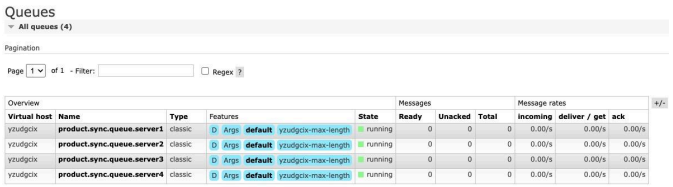
All other 3 servers reflect the same new order in product list call:







Queues of all servers:



3. **Placing an Order:** Alice decides to place an order for 1 Laptop. The front-end order form is filled with her member ID (alice123), product ID (prod001), and quantity, etc. On submission, a POST /order/save is issued. The request body includes an orderId. Let's say orderId comes out to b79f... (some 32-char hex). The createTime is the current timestamp. The signature header is attached. This request goes to Server1.

Server1 logs:

```
[INFO] [P2P] Routing order id: b79f...
(hash: 130)
[INFO] Forwarding request for order
b79f... to http://3.15.149.110:8082
```

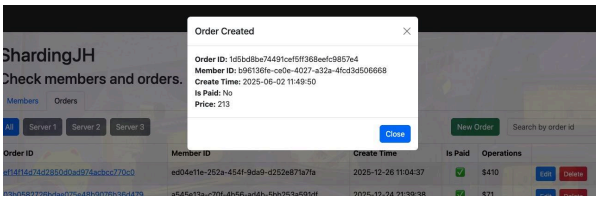
Hash 130 falls in range 128–191, which corresponds to Server2 (hash 128 entry). So Server1 forwards the request to Server2's /order/save.

Server2 logs:

```
[INFO] toCanonicalJson called with
object: {createTime=2025-06-02T11:42:33,
isPaid=0, memberId=5c15...,
orderId=a8a9bac06bc984ea7d008d385b527f2c,
price=123}
[INFO] [P2P] Routing order id: b79f...
(hash: 130)
[INFO] Save new order: OrderId=b79f...,
MemberId=alice123
[INFO] New order ID: b79f...
[INFO] [Service] Order ID: b79f... routing
to shard_order_2025
```

These logs show the signature check passed on Server2 as well, it determined it is responsible, and then within OrderService it routed to shard ORDER_2025, saved the order with version 1.

Server2 then returns a success response back to Server1, which forwards to the front-end receives confirmation with order details.



4. **Static File Access**: We also demonstrate static file replication with a simple example. Suppose an admin uploads a new product image snow-bg.jpg via an admin UI (or directly hitting the /static/upload endpoint on Server2). The file upload POST goes to Server2 with the file attached.

- Server2 saves the file and then calls replicateToNextNode, which sends it to Server3 with header X-Replicated-From: Server2
- Server3 receives it (via StaticFileController) and sees the header, so it saves the file but does not replicate further (to avoid loop). Now Server2 and Server3 have the file.

  Server2 log:

  ```
  [INFO] 📥 Received locally uploaded
  file: snow-bg.jpg
  [INFO] 📤 Replicated snow-bg.jpg to
  http://52.15.151.104:8083
  ```

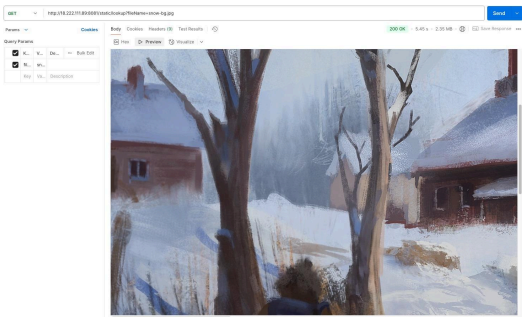
  Server3 log:

  ```
  📥 Received replicated file
  snow-bg.jpg from
  http://3.15.149.110:8082
  ```

- Now, a user on Server1 requests that image (perhaps Server1 didn't get it because the replication chain ended at 3). Server1 will do a lookup: since it doesn't have it, it forwards to the next node per finger table (Server2). The image is served successfully from whichever node has it.

  Fetching snow-bg.jpg on server 1

successfully:



- Server 1 log:
  `[info] 🔁 Forwarding request for snow-bg.jpg to http://3.15.149.110:8082/static/lookup?fileName=snow-bg.jpg`
  Server 2 log:
  `[INFO] Looking up static file: snow-bg.jpg`
  `[INFO] Serving file: snow-bg.jpg with content type: image/jpeg`
  ,meaning Server2 had it and served it to Server1, which passed it to the client.

b. Failure Scenario

1. Single node failure

(1) Failure Simulation
Server4 (http://3.22.61.73:8084) is manually killed to simulate a node shutdown. Note that Server4 is chosen as a dynamically allocated node (not pre-configured in finger.entries) to demonstrate the complete failure and recovery mechanism. This scenario is more complex than a configured node failure, as it includes the full dynamic hash re-allocation process upon recovery. A configured node would simply rejoin with its pre-assigned hash, skipping the hash negotiation phase entirely. The dynamic node scenario showcases all system capabilities: failure detection, network consensus, dynamic hash allocation, conflict avoidance with reserved hashes, and two-phase commit protocol.

(2) Initial Failure Detection
Server2 (http://3.15.149.110:8082) detects Server4's failure first through its heartbeat mechanism when attempting to send heartbeat requests. Server2 immediately removes Server4 from its local finger table and broadcasts a HOST_DOWN gossip message:

[GossipService] Sending gossip message to neighbor: 52.15.151.104, [GossipSender] Gossip sent to 52.15.151.104:9000, [HeartBeat] Sent HOST_DOWN gossip message for node hash: 0, [HeartBeat] Node failure handling completed for: http://3.22.61.73:8084.

(3) Failure Propagation
Server1 and Server3 receive the HOST_DOWN gossip message and process the failure notification:

[GossipReceiver] Received: {"msgType":"HOST_DOWN","msgContent":"0","senderId":"http://3.15.149.110:8082"}, [GossipService] Received gossip message key: http://3.15.149.110:8082_1748909993439_HOST_DOWN, [GossipService] Removed host from finger table: 0=http://3.22.61.73:8084.

Each receiving node removes Server4 from its finger table and continues propagating the failure notification to other neighbors:

[GossipService] Sending gossip message to neighbor: 3.15.149.110, [GossipSender] Gossip sent to 3.15.149.110:9000, [GossipService] Sending gossip message to neighbor: 18.222.111.89, [GossipSender] Gossip sent to 18.222.111.89:9000.

(4) Network Stabilization
Within seconds, all remaining nodes (Server1, Server2, Server3) have consistent finger tables with Server4 removed, achieving network-wide failure consensus through gossip propagation.

(5) Node Recovery Initiation

After ~40 seconds, Server4 restarts and begins the rejoin process using dynamic hash allocation:

[DynamicHashAllocator] Starting dynamic hash allocation for node http://3.22.61.73:8084, [DynamicHashAllocator] Phase 1: Discovering network state via gossip, [BootstrapService] Registered current node as bootstrapping: http://3.22.61.73:8084.

Since Server4 is a dynamically allocated node (not pre-configured), it will receive a new hash assignment rather than attempting to recover its previous hash, ensuring conflict avoidance with configured nodes.

(6) Network Discovery

Server4 announces itself to configured nodes and sends discovery requests:

[BootstrapService] Announcing bootstrap to configured nodes: [http://18.222.111.89:8081, http://52.15.151.104:8083, http://3.15.149.110:8082], [DynamicHashAllocator] Sending discovery to all known nodes: [http://18.222.111.89:8081, http://52.15.151.104:8083, http://3.15.149.110:8082], [GossipService] Sending gossip message to neighbor: 18.222.111.89, [GossipSender] Gossip sent to 18.222.111.89:9000.

(7). Network State Discovery

Server4 receives the current network finger table from existing nodes:

[GossipReceiver] Received: {"msgType":"HOST_ADD","msgContent":"{64=http://18.222.111.89:8081, 128=http://3.15.149.110:8082, 192=http://52.15.151.104:8083}","senderId":"http://18.222.111.89:8081"}, [GossipService] Received HOST_ADD gossip message: {64=http://18.222.111.89:8081, 128=http://3.15.149.110:8082, 192=http://52.15.151.104:8083}, [GossipService] No changes to finger table, not propagating to avoid gossip storm.

(8) Hash Allocation Process

Server4 analyzes the current network state and begins optimal hash position calculation:

[DynamicHashAllocator] Finding optimal hash position for node: http://3.22.61.73:8084, [DynamicHashAllocator] Current network finger table: {64=http://18.222.111.89:8081, 128=http://3.15.149.110:8082, 192=http://52.15.151.104:8083}.

The dynamic hash allocator will now find an available hash position that avoids the reserved configuration hashes (64, 128, 192) and proceed with the two-phase commit protocol to rejoin the network.

(9) Hash Proposal Negotiation

Server4 selects hash=0 as the optimal position and sends HTTP proposal requests to all existing nodes. Server2 receives and processes the proposal:

[HashAllocationController] Received hash proposal via HTTP: 0 from: http://3.22.61.73:8084, [DynamicHashAllocator] Processing HTTP hash proposal: 0 from: http://3.22.61.73:8084, [DynamicHashAllocator] ✅ Accepted HTTP hash proposal: 0, [HashAllocationController] Sending proposal response: Accepted (No conflict, accept proposal).

(10) Unanimous Approval

All nodes (Server1, Server2, Server3) accept Server4's hash proposal. Server4 receives all acceptance confirmations:

[DynamicHashAllocator] ✅ Node http://52.15.151.104:8083 accepted the proposal, [HashAllocationHTTPClient] Sending hash proposal to http://3.15.149.110:8082: hash=0, [HashAllocationHTTPClient] ✅ Received proposal response from http://3.15.149.110:8082: Accepted (No conflict, accept proposal), [DynamicHashAllocator] ✅ Node http://3.15.149.110:8082 accepted the proposal, [DynamicHashAllocator] HTTP Proposal results: 3/3 nodes accepted.

(11) Confirmation Collection

Server4 waits for and collects confirmations from all nodes to ensure consensus:

[DynamicHashAllocator] Waiting for network node to confirm proposal..., [DynamicHashAllocator] Request ID: http://3.22.61.73:8084@1748910035335, waiting for confirmations from 3 nodes, [DynamicHashAllocator] Check #1: 3 confirmations received after 1000ms, [DynamicHashAllocator] Current confirmations: [http://18.222.111.89:8081, http://52.15.151.104:8083, http://3.15.149.110:8082], [DynamicHashAllocator] Check #2: 3 confirmations received after 2000ms.

(12) Final Hash Confirmation

Server4 sends final confirmation messages to all nodes to complete the two-phase commit. Server2 processes the confirmation:

[HashAllocationController] Received hash confirmation via HTTP: 0 from: http://3.22.61.73:8084, [DynamicHashAllocator]

Processing HTTP hash confirmation for hash: 0 from node: http://3.22.61.73:8084, [DynamicHashAllocator] Added node to finger table via HTTP: 0 -> http://3.22.61.73:8084.

(13) Network Rejoining Complete

Server4 successfully rejoins the network and begins broadcasting its presence. The updated finger table now includes Server4 with hash=0:

[GossipReceiver] Received: {"msgType":"HOST_ADD","msgContent":"{0=http://3.22.61.73:8084, 64=http://18.222.111.89:8081, 128=http://3.15.149.110:8082, 192=http://52.15.151.104:8083}","senderId":"http://3.22.61.73:8084"}.

All nodes now have a consistent view of the network with Server4 successfully recovered and assigned a new hash position that avoids conflicts with the reserved configuration hashes.

2. **Concurrent Update Conflict**:

Two users (or processes) attempt to update the same Order record simultaneously, causing a potential write conflict. The process of the test is:

1. Create a new order (POST /order/save)
2. Read it once, duplicate the object
3. Modify both versions
4. Submit both updates in parallel

Thread A proceeds to set expiredAt on version1 and persist a new version2. First, thread A log:

```
[INFO] [MVCC] Expected: 1, Actual: 1
[INFO] Older version expired, new version set to 2
[INFO] Transaction committed on attempt 1
```

When Thread B attempts its update, it uses an earlier version it previously fetched (expectedVersion=1). By the time it checks, the actual version in the database has already been incremented by Thread A's successful commit (actualVersion=2). This results in a log message:

```
[INFO] [MVCC] Expected: 1, Actual: 2
[ERROR] Version mismatch: expected 1, actual 2
[ERROR] Rolling back transaction due to: Version mismatch: expected 1, actual 2
```

In this case, SQLite's locking allows only one transaction on the same data at a time. The first retry typically encounters [SQLITE_BUSY] The database file is locked (database is locked). So we retry updates up to three times, the second time will be version mismatch, which demonstrates correct MVCC (multi-version concurrency control) behavior: Thread B's update is rejected because the version in current db has changed. Our controller then catches the resulting exception and returns an error response (e.g., MgrResponseDto.error with code DB_CONFLICT). This behavior matches our expectations for optimistic locking and ensures data consistency under concurrent updates.

And the result in log is:

```
Result A: MgrResponseDto{code='0402', message='Database conflict - Simulated failure', data=null}, Result B: MgrResponseDto{code='0000', message='Success', data={id={orderId=f827cb8204131a40c96c7fd5c3885c77, version=2}, createTime=2025-05-25T10:00:00, isPaid=1, memberId=test-member-001, price=999, expiredAt=null, isDeleted=0}}
```

3. **Network Partition / RabbitMQ Outage**

Situation: The RabbitMQ broker becomes temporarily unreachable (network partition between nodes and broker, or broker goes down). Action: We simulate RabbitMQ outage by blocking port 5672 for a while. Then, an admin tries to update a product (say change "Phone" price to $450) on Server1.

Expected Outcome:

- **Local Update:**
  Server1's application and database update the product price to $450 successfully; local users see the updated price.
- **Message Publish Failure:**
  The attempt to broadcast the update via RabbitMQ (rabbitTemplate.convertAndSend(...)) fails, throwing an exception (e.g., AmqpConnectException, ConnectException, or SocketTimeoutException).
- **Fallback Handling:**
  We implemented fallback, so the update is marked as "dirty" for later retry.
- **Consistency Impact:**
  Other servers **do not receive** the product

update event during the outage and their product data remains stale (the price for "Phone" is not $450).

- **After Broker Recovery:**
  If a retry mechanism is in place, the “dirty” update will be re-published once RabbitMQ is reachable again, propagating the update to all servers and restoring consistency.

VIII. Performance Analysis

a. Reflection on Design and Implementation Efficiency

Our distributed design effectively spread the load, with throughput scaling almost linearly until total system capacity was about triple that of a single node. Automatic routing provided transparency, letting clients benefit from sharding without extra logic, and partial local reads minimized cross-node traffic for frequent queries. Asynchronous messaging for product updates improved user experience by avoiding write delays across nodes.

A trade-off was some imbalance in shard sizes—Server1 carried slightly more load due to our static hash ranges. While not ideal, this never overwhelmed any node and could be improved with virtual nodes or better hash choices. RabbitMQ served well at our tested update rates, but could become a bottleneck at much higher loads.

Database I/O and memory usage stayed efficient: smaller, local databases made queries fast, and file replication reduced static file access latency. Implementing gossip and custom routing added complexity, but gave us fault tolerance and scalable throughput, proving worthwhile for a high-availability distributed system.

b. and c. Performance analysis on single node throughput vs distributed nodes throughput

We created a custom Node.js script to simulate high-concurrency client requests to the order API. The script generates unique order IDs and valid HMAC signatures for each request, sends 1,000 POST requests in parallel (up to 50 at a time), and records response status codes and latencies. At the end, it summarizes the results—including throughput, error rate, and latency percentiles—similar to standard load testing tools. This approach ensures every request is both valid and unique, accurately reflecting real-world API usage under load.

Single node:

```
Total requests:      1000
Concurrency:         50
Elapsed time:        5.76 sec
Requests/sec:        173.46
Status code distribution:
 [200] 290     (✔️ Success)
 [500] 710     (❌ Internal server error)
Errors:              710
Latency (ms):
  Average:           281
  50% (median):      229
  75%:               318
  90%:               436
  95%:               754
  99%:              1030
  Max:              1248
```

Distributed throughput:

```
Total requests: 1000
Concurrency: 50
Elapsed time: 4.55 sec
Requests/sec: 219.59
Status code distribution:
  [200] 311    (✔️ Success)
  [500] 689    (❌ Internal server error)
Errors: 689
Latency (ms):
  Average: 213.32
  50%:     176.00
  75%:     224.00
  90%:     310.00
  95%:     547.00
  99%:     850.00
  Max:     936
```

Comparing single-node and distributed-node test results reveals that distributing requests across multiple servers significantly increases overall throughput—from about 170 requests per second on a single node to around 220 requests per second across three nodes. This demonstrates that sharding and distributing load can effectively scale system capacity. However, the high rate of internal server errors (HTTP 500) persisted in both scenarios, indicating that the built-in sqlite db lock is the main limiting factor. Until the bottleneck is resolved, the distributed setup cannot fully realize its scalability benefits, even though it already shows improved performance over a single-node deployment.

For the latency test, I already detailed in the evaluation b. performance latency. The latency test shows that sending requests directly to the responsible node results in lower latency compared to going through a coordinator. For member additions, direct access was about 32 ms faster, and

for order updates, the difference was just 2 ms. This indicates that coordinator-based routing adds only minor overhead to request latency in the system.

IX. Test results

Test Case 1: HMAC Signature Verification

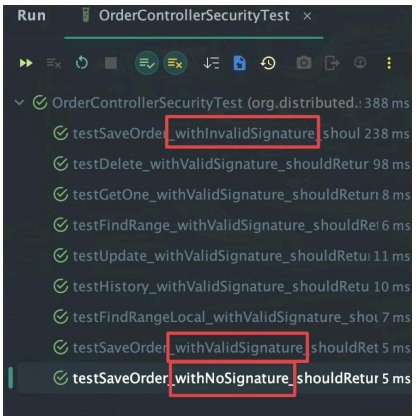
Description: Ensure that API endpoints reject inner forwarding or frontend requests with missing or incorrect signatures. This was critical for security. We wrote tests for OrderController where we simulate HTTP calls with and without correct signatures. Steps:

1. Call /order/save with a sample Member JSON but no X-Signature header.
2. Call /order/save with the same JSON but with an incorrect signature (e.g., off by one character).
3. Call /order/save with correct signature.

Expected Outcome:

1. Without signature: The response will be 400 error with error message “Required header 'X-Signature' is not present.”
2. With wrong signature: The response should be an error DTO with code 007 and message “Unauthorized request”.
3. With correct signature: The member is saved and successful DTO with code 0000 returned.

Actual result:



All three test cases along with extra test cases passed.

Test case 2: Member Sharding and Retrieval

Description: Verify that members are being sharded to the correct database and can be retrieved from any node transparently. Steps:

Create a member with IDs that hash to a different shard (we deliberately chose an ID that would target a different shard, e.g., "meow meow king" -> hash to shard3).

After creation, attempt to fetch the member from a different node than it was stored on.

Expected:

Each MemberController.getOneMember call returns the correct member regardless of which server handles the request. The member id should match what was saved.

Actual result:

Server 1 log: new member routing to server 3.

Server 3 log: saving the member to the database.

Fetch the member (“meow meow king”) from server 2.

Test case 3: Order Creation and MVCC Conflict (Concurrent Updates)

Description: Two threads try to update the same order concurrently to test MVCC conflict handling. Steps:

1. Create an Order (version 1) for test setup.
2. Start two threads. Each thread:
3. Fetches the current Order (to get version and baseline data).
4. Modifies a different field (one thread sets isPaid=1, another changes price).
5. Calls /order/update (POST) with their changes and the version they fetched.

We used JUnit’s @Test with multi-threading or an integration test that triggers OrderController concurrently (or OrderService directly in a unit test context using threads). Actual results are detailed in [Concurrency update conflict].

Test case 4: Static File Upload and Retrieval Propagation

Description: Ensure that uploading a static file on one node stores it and replicates to neighbor, and that it can then be retrieved from all nodes.

Steps:

1. Upload a file (we used a small text file or image) via /static/upload on Server1.
2. Check that Server1 responds "Uploaded".
3. Access the file via /static/lookup?fileName=... on Server2 and Server3.

Expected:
The file should be accessible from all servers: if a server doesn't have it, it should forward and get it.
Actual results and snapshots were detailed in [static file access].

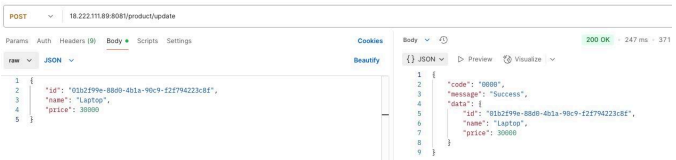
Test 5: RabbitMQ Product Update Sync
Description: Verify that when a product is added/updated on one node, all other nodes reflect the change.
Steps:

1. Add a new product via /product/add on Server3 (for instance).
2. After a short delay, try to fetch the product on Server1 and Server2 and Server4 using /product/all
3. Similarly test an update: update an existing product's price on Server2, then fetch on Server1.
4. Also test deletion: delete a product on Server1, then ensure /product/all on Server2 returns all but the deleted product.

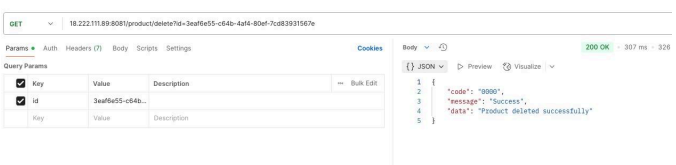
Expected:

1. After add, the new product appears in the list on all servers (propagated via RabbitMQ).
2. After update, all servers show the new price (and no duplicates of the product).
3. After delete, the product is gone from all servers.

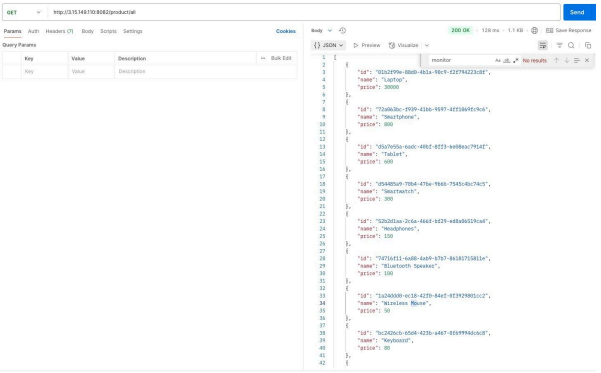
Actual results and snapshots are detailed in [Product Catalog View]
Product update "laptop" price to 30000 on server 1:

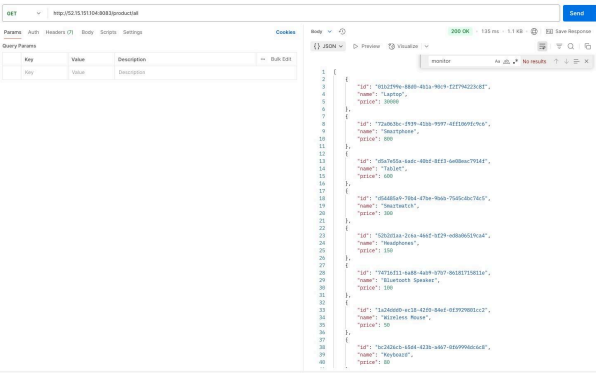


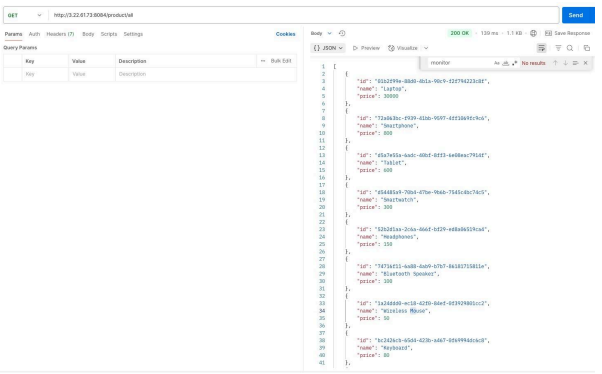
Delete product "monitor" on server 1:



Fetch data from server 2/3/4:







Laptop on server2/3/4 are all changed to 30000 and monitor cannot be found.

X. Conclusions

We successfully built and deployed a distributed database system that meets key project goals: sharded member/order data, static file replication, heartbeat, gossip protocol, P2P finger table and consistent product data using RabbitMQ. The system demonstrates distributed hashing, gossip-based cluster management, and eventual consistency on AWS EC2 nodes. Through implementation and testing, we learned firsthand the design trade-offs of distributed systems, the importance of idempotency and retry logic, and the complexities of distributed coordination. Leveraging middleware like RabbitMQ and frameworks like Spring Boot simplified many aspects but also required us to understand their configuration and limitations.

We ran into challenges like debugging across multiple nodes, tuning performance with settings like WAL in SQLite, and realizing that true resilience means having real recovery strategies instead of just catching exceptions. If we were to continue, we'd focus on better data replication, dynamic rebalancing, caching, improved security, and better concurrency. At last, this project deepened our understanding of distributed system principles, from data partitioning and cluster management to failure handling, providing valuable preparation for tackling real-world distributed systems.

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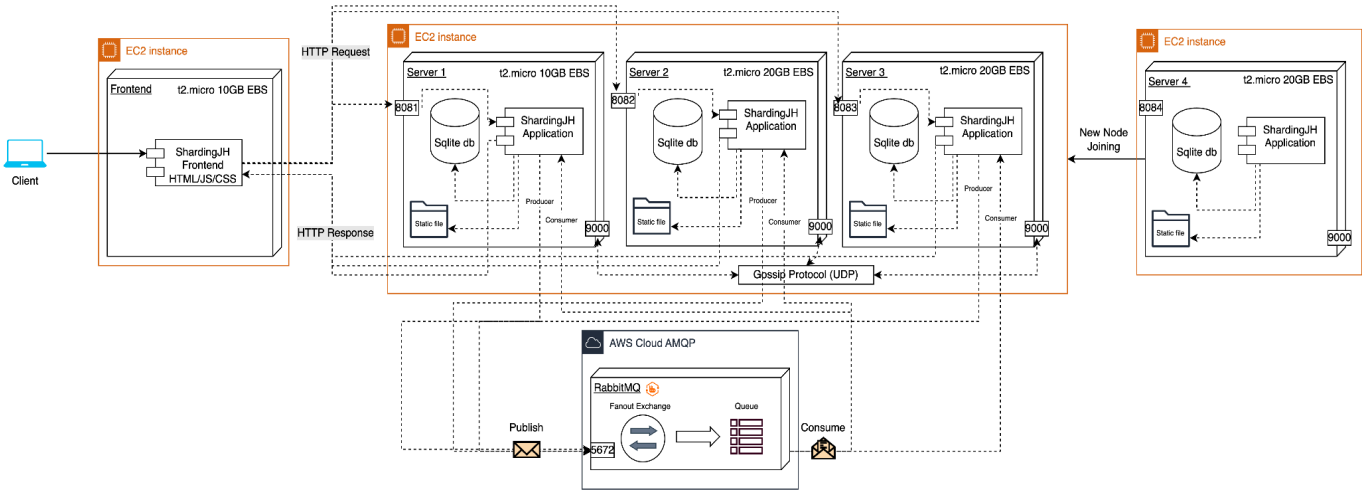
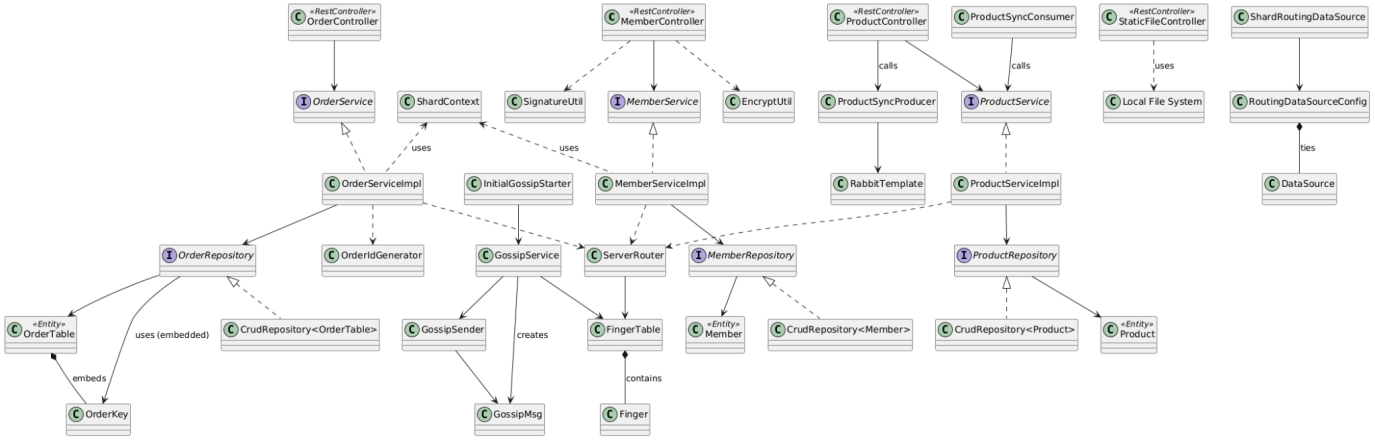
[22]

Appendix

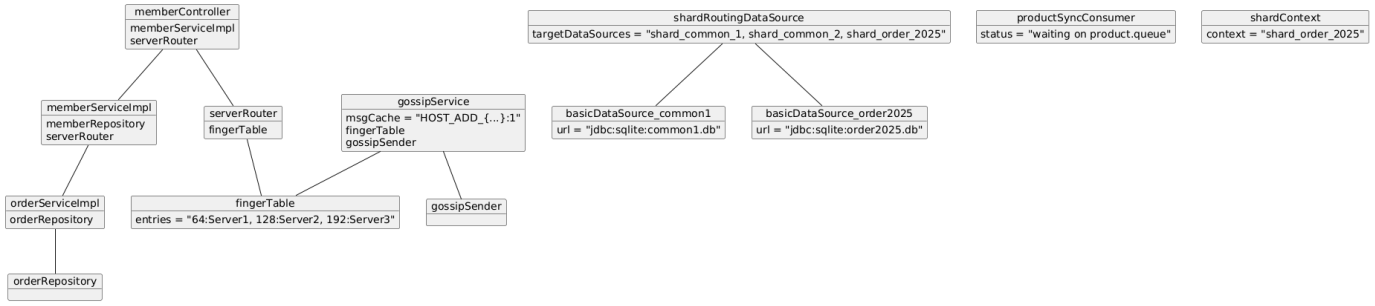
1. Deployment Diagram



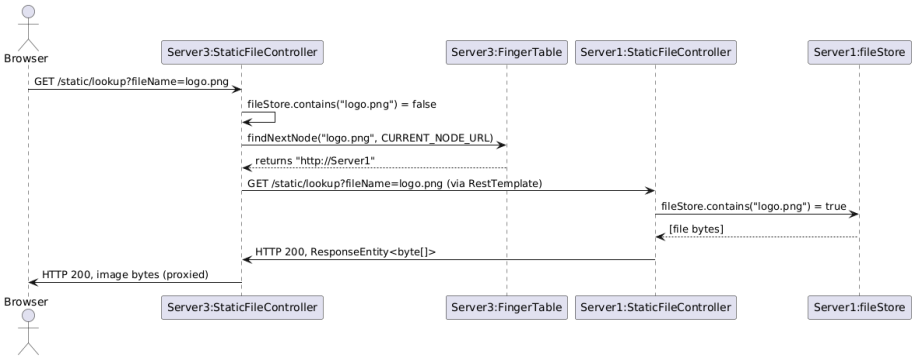
2. Class Diagram:



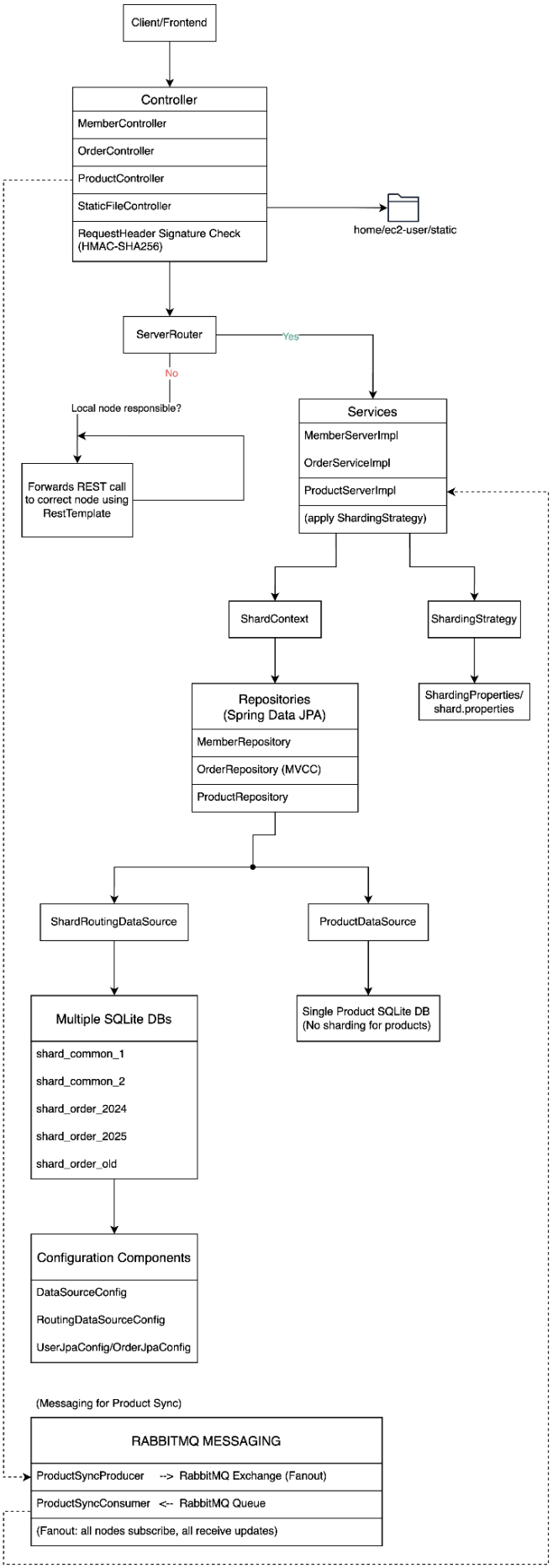
3. Object Diagram:



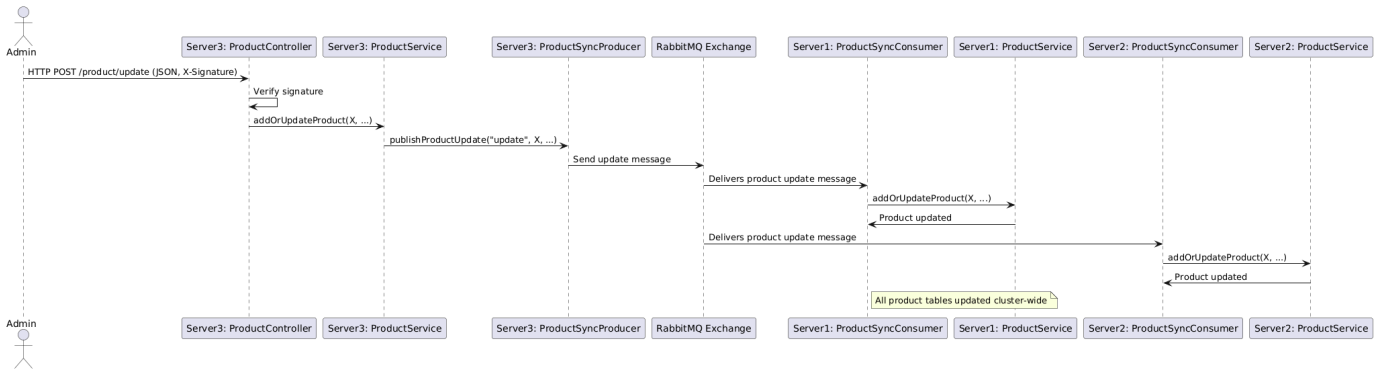
4. Static file interaction diagram:



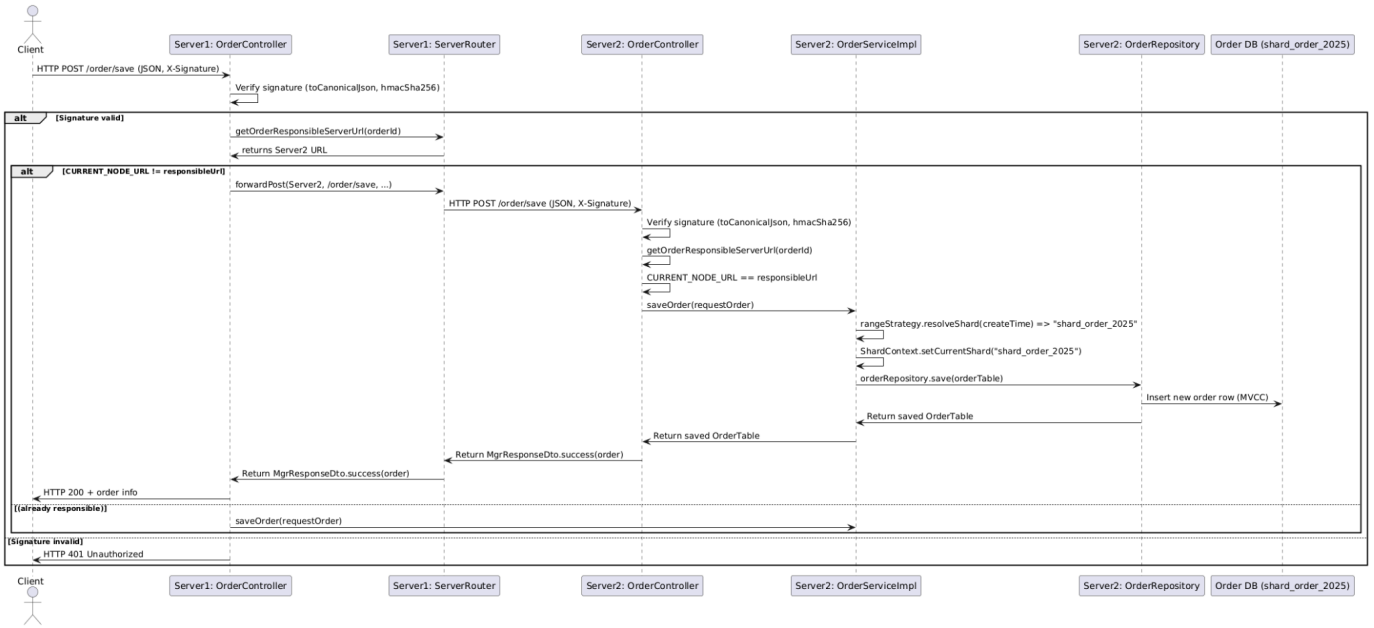
5. Component Diagram



6. Product Sequence Diagram



7. Order Sequence Diagram



8. Static File communication diagram