Scalable Sharding for Concurrency Conflict Resolution in Blockchain Systems

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Contents

1 Acknowledgements

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2 Introduction

Scalability and concurrency control are fundamental challenges in distributed systems, particularly within blockchain architecture. As the technology matures and sees broader adoption, traditional monolithic blockchains with global consensus mechanisms increasingly show performance and flexibility limitations, especially under high transaction volumes and contention for shared resources.

To overcome these constraints, this project implements a sharded blockchain architecture that supports parallel transaction processing. It separates execution responsibilities across shards, coordinates cross-shard communication, and maintains consistency without introducing bottlenecks. The aim is to demonstrate how sharding and intelligent routing enhance throughput, resolve concurrency issues, and eliminate common pitfalls such as deadlocks and locking conflicts. The resulting system is a modular prototype that visually and functionally simulates blockchain behaviour across sharded, non-sharded, and cross-shard execution models.

3 Purpose, Operation and Validation

This project implements a modular and extensible blockchain simulator designed to explore how sharded execution can overcome the scalability and concurrency challenges faced by traditional blockchain systems. Conventional ledgers suffer from performance bottlenecks due to their reliance on a global state, sequential transaction ordering, and synchronous consensus. These limitations restrict throughput, introduce latency under high load, and leave the system vulnerable to deadlocks when multiple transactions compete for shared resources.

To address these issues, the proposed platform introduces a hybrid sharding model that supports both monolithic (non-sharded) and parallel (sharded) transaction workflows. This enables a comparative analysis of transaction behaviours, latency patterns, and concurrency resolution across execution modes.

Operational Design

The system architecture consists of three tightly integrated components:

Frontend Interface (React + ReactFlow): Provides an interactive, real-time visualisation of the blockchain state. Nodes (blocks) are represented graphically and colour-coded based on shard membership. Users can initiate transactions, configure shards, and observe live execution feedback, including status updates, propagation time, and concurrency behaviour.

Go-based REST API Backend: Serves as the coordination and execution layer, responsible for routing transactions, handling sharded execution logic, logging metadata, and managing the internal blockchain state. It exposes endpoints for transaction submission, deadlock simulation, node-to-shard assignments, and blockchain resets. The stateless design follows microservice principles, allowing for horizontal scalability and modular extension.

Dockerised Execution Layer: Simulates isolated nodes within containers, enforcing shard boundaries and enabling parallel execution environments. This abstraction supports concurrent workloads and provides the infrastructure to test execution across multiple logical partitions.
The system supports two distinct execution flows:

Non-Sharded Mode: Transactions are restricted to nodes within the same shard, allowing for deterministic execution without inter-shard coordination. This models traditional blockchain behaviour.

Sharded Mode: Transactions span across shards and are processed concurrently. Cross-shard routing is handled asynchronously, with each shard managing its own queue and consistency guarantees. This mode enables higher throughput and reduces contention.

A dedicated deadlock simulation mode is provided to demonstrate the shortcomings of non-sharded models. It programmatically induces circular waits between transactions to highlight execution stalls and contrast them with the isolation and concurrency benefits offered by the sharded approach.

Validation and Evaluation

The platform has been validated through a combination of functional testing, live visualisation, and structured transaction logging. Key validation activities include:

Correctness Checks: All transaction paths were tested to ensure that execution adheres to shard boundaries, and that logs reflect expected outcomes (success, failure, execution time).

Deadlock Testing: The `/deadlocksim` endpoint was used to simulate contention scenarios. In contrast to sharded execution, which isolates and resolves such conflicts, non-sharded mode reliably demonstrates blocking behaviour under circular wait conditions.

Performance Observation: Through real-time analytics (via Firestore and frontend logging), differences in throughput and latency were observed and compared between intra-shard, inter-shard, and non-sharded transactions.

Recovery and Traceability: Firestore-backed persistence enabled full recovery of system state across sessions. This allowed for replaying transaction histories and conducting post-hoc validation of concurrency outcomes.

Together, these validation mechanisms demonstrate that the system meets its goals: to enable real-time exploration of concurrency control in blockchain systems, to highlight the scalability advantages of sharded execution, and to serve as an educational and experimental platform for future work.

3.1 Data Model

The data model at the core of this system is composed of blocks, transactions, and logs that together represent the state and flow of the blockchain. Each block acts as a container for a set of validated transactions and is assigned a unique index, timestamp, shard ID, and hash. Blocks are colour-coded by shard in the frontend and linked visually and logically to their predecessor, forming an ordered chain within each shard.

Transactions are structured JSON objects containing fields such as source, target, data payload, and an '$is_sharded$' flag to denote the nature of the transaction.

For non-sharded transactions, both source and target must reside in the same shard, while for sharded transactions, source and target may span multiple shards.
This distinction drives validation logic on the back-end and influences how transactions are processed and grouped.

All submitted transactions are assigned unique identifiers and temporarily marked as pending. These are tracked using a status map that is regularly updated based on back-end confir-

mations. Once a transaction is successfully processed, its associated blocks are updated, and visual feedback is provided in the user interface.

The blockchain state is maintained in memory and updated in real time via API responses. Each block includes metadata about its shard membership, peers, current hash, and the transactions it holds. This enables consistent representation in both logic and visualisation layers.

A transaction log system is also included to assist with traceability and debugging. This log records recent transaction events, including timestamps, source-target pairs, transaction IDs, and statuses such as completed or pending. These logs are accessible through the UI for user inspection and academic evaluation.

3.2 Quality Assurance

To ensure the correctness, maintainability, and reliability of the software developed in this project, several quality assurance (QA) practices were followed throughout the development lifecycle.

Version Control: Git was used for source control and versioning. The project was managed via a GitLab repository hosted by Queen's University Belfast. This allowed for commit tracking, rollbacks, issue tracking, and collaborative features such as branching and pull requests when testing new functionality. Frequent commits were made to document changes in both backend logic and frontend features.

Code Style and Convention: JavaScript/React and Go code followed consistent naming conventions and structural patterns. Indentation, naming, and modular design principles (such as reusable components and separation of concerns) were enforced manually to maintain code readability. The backend in Go adhered to idiomatic Go standards, while the frontend followed modern ReactJS and ReactFlow usage patterns.

Automated Testing and Validation: Although formal unit testing frameworks were not extensively used due to the prototype nature of the project, all core functions were validated through live simulation in the browser and inspection of blockchain state updates. Both non-sharded and sharded transaction workflows were tested under different shard configurations and workloads.

Deadlock Testing: A dedicated deadlock simulation mode was implemented as a functional test feature to validate concurrency logic and demonstrate lock contention scenarios. This tool helped confirm the correct separation of transaction flows between shards and served as an educational validation mechanism.

Manual UI Testing: The React frontend was manually tested across different resolutions and usage scenarios. Node selection, transaction sending, log tracking, and shard configuration were verified interactively using the in-browser interface. Unexpected behaviours were logged and iteratively fixed.

Deployment and Testing Environment: The system was deployed using Docker to simulate isolated nodes, and tested within a WSL2 environment on Windows to reflect a realistic cross-platform setup. This ensured functionality, traceability, and reproducibility throughout development.

4 Languages and Frameworks Used

4.1 Golang (Go)

Purpose: Backend language for logic, concurrency, and RESTful services. Chosen for its lightweight goroutines, strong typing, and built-in JSON handling. Key usage includes `working_main.go` as the entry point with Gin for routing, goroutines for transaction execution, mutexes for shared-state access, and graceful shutdown logic for Docker compatibility.

4.2 React (JavaScript / JSX)

Purpose: Frontend framework enabling interactive UIs. React's component-based design, hooks (`useState`, `useEffect`), and ReactFlow integration allow dynamic visualisation of blocks, real-time feedback, and modal-based interaction for sharding, deadlocks, and transactions.

4.3 ReactFlow

Purpose: Visualisation of blockchain nodes and edges. It provides dynamic rendering of blocks as draggable nodes and edges with support for custom node types such as "Shard Bubbles," including logic for click interactions (e.g., Ctrl click multi target).

4.4 Gin Web Framework (Go)

Purpose: High-performance HTTP router. All backend endpoints (`/addTransaction`, `/shardTransactions`, `/deadlocksim`, etc.) are handled via Gin. Middleware such as CORS is used for React compatibility, and server shutdown is handled with context aware cancellation.

4.5 Docker API (Go SDK)

Purpose: Simulate distributed nodes. Running containers are scanned via `cli.ContainerList()`, then transformed into blocks using `addBlock()`, enabling realism in blockchain deployment scenarios.

4.6 Firebase + Firestore (GCP)

Purpose: Persistent cloud-based logging. The `firebase.go` file initialises the Firestore client. `SaveTransactionToFirestore()` logs execution metadata, and `LoadTransactionsFromFirestore()` repopulates the UI state on restart.

4.7 HTML + TailwindCSS (via JSX)

Purpose: UI styling with utility first design. Tailwind styles modals, buttons, overlays, and transaction status messages, supporting rapid development and dark mode.

4.8 JSON

Purpose: Frontend-backend communication format. All request/response payloads, Firestore documents, and Docker interactions use JSON encoding and decoding.

4.9 Shell / WSL2

Purpose: Command line execution and testing. Used for launching Docker containers, backend services, and manual testing with curl and logging tools.

Technology Summary Table

Technology	Role	File(s) Used
Go (Golang)	Backend logic, concurrency, API	`working_main.go`, `block.go`, `sharding.go`
React	Frontend logic and state	`Blockchain_Interact.js`
ReactFlow	Blockchain visualisation (nodes/edges)	`Blockchain_Interact.js`
Gin (Go)	REST API framework	`working_main.go`
Firebase	Cloud-based persistent logs	`firebase.go`
Docker API	Block simulation from containers	`working_main.go`, Docker CLI
Tailwind CSS	UI Styling via JSX	JSX components
JSON	Data serialisation (frontend/backend)	All API interactions

Table 1: Summary of Technologies Used

5 Key Features

This project incorporates several core features that collectively demonstrate how **sharding** can be applied to address **blockchain scalability** and **concurrency conflicts**, while integrating **real-time persistence** to ensure fault tolerance and long-term state recovery. The system is composed of a visual frontend, a scalable backend, and persistent cloud storage, working together to simulate and analyse transaction flows across a sharded blockchain architecture.

1. Interactive Blockchain Interface with Shard Colouring

The frontend interface, developed using `React` and `ReactFlow`, displays a spider-web layout of the blockchain, where each block is represented as a node. Blocks are colour-coded according to their shard assignment, providing immediate visual cues for identifying cross-shard or intra-shard transactions.

This interactive interface enables:
Block/node selection: Users can define source and target nodes for transactions.
Transaction execution path preview: Visualise transaction routing across the blockchain.
Shard-aware colouring: Easily distinguish shards based on node colour.
Real-time execution logs: View transaction status, execution time, and latency as they occur.

Users can test both sharded and non-sharded transaction behaviours, observe parallelism in execution, and monitor performance metrics live.

2. Real-Time Persistent Storage and Execution Logging

To support fault tolerance, auditing, and live analytics, the system integrates with `Firebase Firestore` for **real-time, persistent storage** of all blockchain transactions. Whether a transaction is sharded or non-sharded, it is automatically recorded upon submission to ensure durability and transparency across sessions.

Each logged transaction captures the following metadata:
Transaction ID Source and target nodes Type: Sharded or Non-Sharded, **Execution time** (in milliseconds),
Timestamp, **Message payload**

This persistent storage layer enables the system to:
Reload the full blockchain state after shutdown
Enable **cross-session auditability and traceability**
Support **live analytics and real-time visual updates** in the frontend

Backend Implementation: Firestore Logging in Go

The logging mechanism is implemented within the backend using the official Firestore SDK. After each transaction is executed—regardless of type—a structured log entry is saved to the Firestore database.

The following Go snippet demonstrates this process:

```go
import (
    "context"
    "log"
    "time"
    "cloud.google.com/go/firestore"
    "google.golang.org/api/option"
)

type TransactionLog struct {
    ID string `firestore:"id"`
    Source int `firestore:"source"`
    Target int `firestore:"target"`
    Type string `firestore:"type"` // "Sharded" or "Non-Sharded"
    Message string `firestore:"message"`
    ExecutionTime int `firestore:"execution_time"` // milliseconds
    Timestamp time.Time `firestore:"timestamp"`
}

var firestoreClient *firestore.Client

func InitFirestore() {
    ctx := context.Background()
    sa := option.WithCredentialsFile("path/to/serviceAccountKey.json")
    client, err := firestore.NewClient(ctx, "your-project-id", sa)
    if err != nil {
        log.Fatalf("Failed to create Firestore client: %v", err)
    }
    firestoreClient = client
}

func SaveTransactionToFirestore(logEntry TransactionLog) error {
    ctx := context.Background()
    _, _, err := firestoreClient.Collection("transactions").Add(ctx, logEntry)
    return err
}
```

Listing 1: Logging Blockchain Transactions to Firebase Firestore

This function is invoked immediately after each transaction is processed. By maintaining a complete transaction history in Firestore, the system ensures resilience, enables post-event analysis, and allows for real-time visualisation of transaction metrics in the frontend interface.

3. Sharded vs. Non-Sharded Execution Modes

The system supports two distinct transaction execution models: **non-sharded** (monolithic) and **sharded** (partitioned), each representing fundamentally different approaches to concurrency and scalability in blockchain systems.

Non-Sharded Transactions execute within a globally shared state. All nodes contend for the same pool of resources, such as account balances or memory space. Transactions are processed sequentially, and concurrency is managed using global locking mechanisms. This design leads to high contention and an increased risk of deadlocks, especially when multiple transactions access shared resources simultaneously.

Sharded Transactions, on the other hand, operate in parallel across multiple independent shards. Each shard maintains a localised subset of the blockchain state and processes transactions within its partition autonomously. This decentralised architecture dramatically improves system throughput and mitigates contention by isolating execution contexts.

- **Intra-shard Transactions**: Occur when both the source and target nodes reside within the same shard. These transactions leverage the shard's isolated execution environment and are executed in parallel batches. Since they operate on local state, they avoid the overhead of inter-shard coordination and maintain high throughput even under heavy load.
- **Cross-shard Transactions**: Occur when the source and target nodes belong to different shards. These transactions are coordinated asynchronously through non-blocking messaging protocols (e.g., RESTful APIs like `/crossShardTransaction`). The system routes transaction segments to the corresponding shard buffers and allows each shard to process its portion independently. This approach preserves consistency while eliminating circular wait conditions.

Avoiding Deadlocks via Sharding

Deadlocks in traditional blockchain systems stem from circular wait dependencies caused by global locks. For example, Transaction A may lock Node X and wait on Node Y, while Transaction B simultaneously locks Node Y and waits on Node X. Such circular dependencies lead to execution stalls and system-level bottlenecks.

Sharding directly addresses this issue through the following mechanisms:

Execution Isolation: Each shard operates independently, managing its own transaction queue and state. This drastically reduces the probability of cross-resource contention that leads to deadlocks.

Asynchronous Coordination: Cross-shard transactions are not subject to global lock acquisition. Instead, they are routed through structured APIs and buffered queues, allowing shards to process them independently and in a serialised manner. This eliminates the mutual waiting patterns that typically result in deadlocks.

Deterministic Resolution: Shards enforce deterministic rules for transaction acceptance and ordering. This predictability supports concurrency control without requiring rollback or global consensus locks.

Execution Workflow and System Behaviour

The backend routes **intra-shard transactions** to the corresponding shard's execution engine where they are processed in parallel.

Cross-shard transactions are decomposed and inserted into each shard's pending queue. Finalisation occurs after both shards process their respective components.

All transactions, regardless of type, are persistently **logged via Firebase Firestore** for recovery, auditability, and performance analysis.

This sharded execution model transforms the blockchain from a sequential, lock-heavy architecture into a distributed, conflict-resilient system. It significantly reduces execution latency, improves throughput, and maintains responsiveness under high-load conditions. Performance evaluations demonstrate that intra-shard transactions achieve the fastest execution, while cross-shard transactions maintain bounded latency without the exponential delay observed in non-sharded systems.

4. Deadlock Simulation for Concurrency Control

To provide a tangible demonstration of concurrency pitfalls in non-sharded systems, the platform includes a dedicated deadlock simulation feature. This tool highlights the challenges of global state contention by programmatically inducing a circular wait condition between two transactions.

Example Scenario:
Transaction A locks Node 1 and waits for Node 2.
Transaction B simultaneously locks Node 2 and waits for Node 1.

This classic deadlock configuration creates an unresolvable dependency cycle, resulting in both transactions stalling indefinitely. The simulation is triggered via a specific backend endpoint (`/deadlocksim`) and visualised in real time through the frontend interface.

Rather than merely describing deadlocks abstractly, this simulation enables users to: Observe how circular wait conditions emerge during concurrent execution.
Analyse the resulting execution stall and its effect on throughput.
Appreciate the need for architectural solutions such as transaction isolation or asynchronous coordination.
While Section 3 explored how sharded execution modes structurally prevent such scenarios through isolation and asynchronous routing, this simulation serves as a pedagogical contrast—visually reinforcing the risks of monolithic designs and the concurrency benefits enabled by sharding.

5. Go-Based REST API Backend Coordination

At the core of the system lies a lightweight backend implemented in `Go`, designed to coordinate all blockchain activity through a stateless, modular RESTful API. This architectural choice supports clean separation of concerns, rapid iteration, and compatibility with frontend clients, making the system both scalable and extensible.

The API exposes endpoints to facilitate a broad range of blockchain operations:
Transaction Submission: Supports both single and batched transactions via endpoints such as `/addTransaction` for non-sharded execution and `/shardTransactions` for parallel execution across shards.
Transaction Execution and Logging: Each processed transaction is logged persistently to Firestore with metadata for recovery, auditing, and analysis.

Shard Assignment Management: The `/assignNodesToShard` endpoint allows dynamic grouping of nodes into shards, enabling experimental reshuffling and performance tuning.

Deadlock Simulation: The `/deadlocksim` endpoint deliberately induces circular wait conditions to demonstrate concurrency conflict scenarios in non-sharded architectures.

Blockchain Reset: The `/resetBlockchain` endpoint allows full reinitialisation of system state, clearing logs, shards, and transactions—useful for repeatable testing or demonstrations.
Stateless Design and Microservice Principles The backend maintains no internal memory between requests; all state management is delegated to external components like Firestore (for persistence) and the frontend interface (for node grouping and view logic). This statelessness ensures:
Horizontal scalability: Multiple backend instances can operate in parallel without risk of conflict.
Fault isolation: Errors in one API call do not propagate or affect other operations.
Deployability: The system can be containerised and deployed using orchestration tools like Docker and Kubernetes.

Stateless Design and Microservice Principles The backend adheres to a stateless architectural model, maintaining no internal memory between requests. All state management responsibilities are offloaded to external systems such as the `Firebase Firestore` for persistent storage, and the frontend interface for node grouping, shard membership, and visual logic.

This stateless design enables high modularity and aligns with modern microservice principles, offering the following advantages:

Horizontal Scalability: Backend instances can be scaled out across multiple nodes or containers without coordination overhead, as no shared memory or local state needs to be synchronised.

Fault Isolation: Failures or exceptions in one API call do not interfere with other requests. Each operation is processed independently, enhancing reliability under load.

Ease of Deployment: The system can be containerised using Docker and orchestrated using Kubernetes or similar platforms, enabling automated rollouts, service discovery, and load balancing.

Developer Agility: Stateless APIs make the system easier to test, debug, and extend: each endpoint can be validated in isolation with predictable behaviour.

5.1 Key Components and Transaction Flow

The platform architecture consists of modular layers designed to handle distinct responsibilities:

Frontend: Built with `React` and `ReactFlow`, enabling interactive visualisation of blocks, shard assignment, and transaction flow.

Backend: A RESTful API in `Go` manages routing, execution, logging, and deadlock simulation.

Execution Layer: Docker containers simulate blockchain nodes for isolated, parallel shard execution.

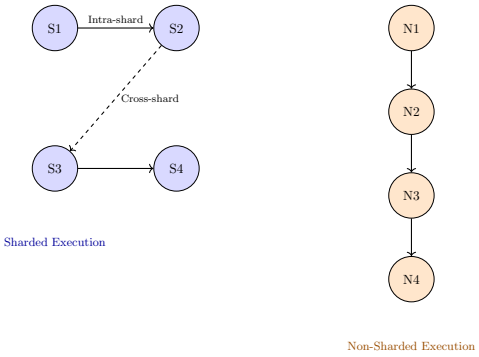

Figure 1: Visual comparison of sharded vs non-sharded transaction flows.

Important Functions

Non-Sharded Transactions: Transactions within the same shard are validated by the frontend before being sent to the backend. If source and target differ in shard, the request is rejected:

```
if (sourceShard !== targetShard) {
  alert("Invalid Non-Sharded Transaction");
  return;
}
await fetch("/addTransaction", {
  method: "POST",
  body: JSON.stringify({ source, target, data, is_sharded: false })
});
```

Listing 2: Simplified Non-Sharded Transaction Logic

Sharded Transactions: Transactions between different shards are grouped and submitted to the backend's `/shardTransactions` endpoint for concurrent processing:

```
const shardSize = 3; const grouped = transactions.slice(0, shardSize);
await fetch("/shardTransactions", {
  method: "POST",
  body: JSON.stringify({ transactions: grouped }) });
```

Listing 3: Sharded Transaction Grouping

These routing policies underpin the system's concurrency model, reducing global contention and enabling scalable blockchain execution across isolated shards.

5.2 Testing Strategy

To ensure the correctness, reliability, and performance of the blockchain simulation platform, a multi-layered testing strategy was employed. This included unit tests for isolated logic verification, integration tests for inter-module behaviour, and system-level evaluations to validate end-to-end functionality under realistic workloads.

Unit Testing

Unit testing focused on validating the correctness of individual backend components in isolation. Go's built-in `testing` library was used in conjunction with manual log tracing to confirm expected behaviour.

Tested Units Included:

`getShardID()`: Confirmed deterministic shard assignment based on modular or prefix-based logic.

`processTransaction()`: Verified correct handling of sharded and non-sharded transactions, including validation of source/target shard membership and propagation metrics.

`SaveTransactionToFirestore()`: Validated successful logging of transaction metadata and proper Firestore document formatting.

`LoadTransactionsFromFirestore()`: Ensured previous system state could be correctly retrieved and restored to support persistence and recovery.

Mock data and simulated delays were used to test transaction execution timing and edge cases such as invalid block IDs or duplicate transactions.

Integration Testing

Integration testing verified the correct interaction across back-end modules (transaction logic, sharding engine, and Firestore logging) and front-end and back-end communication through RESTful APIs.

Scenarios Tested: Transaction Lifecycle: Submission from the front-end triggers back-end execution and logs metadata to Firestore, which is then correctly re-rendered in the React UI. **Shard Assignment Propagation:** Shard reconfiguration via the `/assignNodesToShard` API updates both the back-end logic and the front-end node colouring in real time. **Deadlock Simulation:** The `/deadlocksim` endpoint was tested to ensure it correctly injected pending transactions in a circular wait configuration, visually highlighting stalled execution.

ReactFlow Synchronisation: ReactFlow was dynamically updated in response to blockchain changes, transaction status updates, and shard configuration events.

Integration testing was carried out through Postman, browser-based developer tools (e.g., Chrome DevTools), and manual operation of the front-end to observe consistency between state transitions.

System Testing

System testing validated the complete operation of the platform, encompassing Docker simulation layer, concurrent back-end logic, Firebase persistence, and real-time front-end visualisation.

Key Focus Areas:

Scalability Under Load: Large volumes of transactions were submitted in parallel via the `/shardTransactions` and `/addParallelTransactions` endpoints to test throughput and latency. Execution time, TPS, and finality were benchmarked.

Concurrency Resilience: Mixed workloads with sharded and non-sharded transactions to observe contention patterns and validate the deadlock prevention capability of the sharding model.

Recovery Testing: The back-end state was cleared and successfully reloaded from Firestore logs using `LoadTransactionsFromFirestore()`, demonstrating full recovery support.

Cross-Shard Consistency: Verified that segmented transactions maintained logical consistency across asynchronous execution in separate shards.

Stress testing revealed that intra-shard transactions yielded the highest TPS while cross-shard operations maintained bounded latency, supporting the system's concurrency and scalability goals.

This layered approach to testing ensured that all core features were met. The modular transaction routing to visual analytics allows for in-isolution processing, as well as part of the broader simulation environment.

6 Transaction Metrics and Performance Evaluation

To rigorously evaluate the impact of sharding on blockchain performance and concurrency control, a dedicated metrics and analytics framework was integrated into the system. This section outlines the evaluation objectives, implementation architecture, data flow, visual analytics pipeline, and key insights derived from observed performance patterns across a range of simulated workloads.

6.1 Evaluation Purpose and Metrics

The goal of the evaluation module is to assess how sharding improves system behaviour across several core performance dimensions. Rather than relying solely on theoretical analysis, this framework captures empirical data from both sharded and non-sharded transaction flows, allowing for quantifiable comparisons.

The following metrics are collected for each transaction event:

Execution Time (ms): Measures the time from transaction submission to backend confirmation and block inclusion. This reflects system responsiveness under different loads.

Finality Time (ms): Captures how long a transaction takes to become immutable in the chain. It indicates the system's ability to provide confirmation guarantees quickly.

Propagation Latency (ms): Represents the time it takes for a transaction to be recognised across all blocks/nodes. It relates to communication delay and coordination overhead.

Transactions Per Second (TPS): Tracks throughput in terms of successfully committed transactions per second, which is a key indicator of scalability.

Transaction Type: Labels each transaction as either sharded or non-sharded, enabling disaggregated analysis.

These metrics enable a nuanced understanding of how concurrency control mechanisms perform under stress and how isolated execution (through sharding) enhances or inhibits system behaviour.

6.2 System Implementation Architecture

The performance analysis module is structured around three core subsystems working in synchronisation:

A **ReactJS front-end** built with Recharts provides a rich visual layer, enabling users to monitor and interact with system metrics in real time. It supports toggleable views for sharded vs non-sharded transactions and live updates during simulation.

A **Golang backend**, responsible for executing transactions, calculating durations, and forwarding logs to the database. REST endpoints receive transaction requests, initiate execution via goroutines, and record the resulting performance metrics with precise timestamps.

A **Firebase Firestore database** stores all logs persistently, ensuring continuity across sessions. It acts as a central repository for all metrics and supports real-time syncing with the front-end.

Transaction Log Data Structure (Go)

```
type TransactionLog struct {
  ID           string    `json:"id"`
  Type         string    `json:"type"`
  ExecTime     float64   `json:"execTime"`
  FinalityTime float64   `json:"finalityTime"`
  TPS          float64   `json:"tps"`
  Timestamp    time.Time
}
```

This data structure ensures consistent logging and makes it easy to compare different transaction types during evaluation.

6.3 Interactive Front-end Dashboard

The visual dashboard, defined in the `TransactionMetrics.js` module, is central to the evaluation experience. It offers an intuitive, real-time analytics view that integrates with user-submitted transactions.

Each metric is rendered using appropriate Recharts visual elements:

Execution Time Line Charts: Plot temporal trends in processing delays across transaction types, highlighting relative performance.

Finality and Propagation Charts: Display the commitment and visibility delay per transaction, providing insight into backend coordination and consensus delays.

TPS Graphs: Real-time line graphs visualise throughput over time, reflecting the system's processing capacity and stability.

Stacked Bar Charts: Compare execution and finality times side by side for each transaction type, making inefficiencies immediately apparent.

Pie Charts: Present transaction type distributions, which can shift dynamically based on user interaction and system configuration.

The dashboard supports both *split views*—where sharded and non-sharded metrics are shown separately—and *combined views* for comparative analysis. This dual-mode visualisation helps to identifyutliers, bottlenecks, and consistent trends.

6.4 Observed Trends and Results

Experimental results were obtained by submitting a series of transactions under controlled conditions—first in a sequential, non-sharded mode, and then under a sharded parallel regime. The key findings were:

Execution Time: Sharded transactions completed significantly faster (average ˜1572ms) than non-sharded transactions (˜4186ms), showcasing the benefits of distributed execution.

Finality Time: Confirmation delays were shorter for sharded flows (˜876ms) than for non-sharded ones (˜1700ms), reinforcing the claim that sharding mitigates global locking and consensus delay.

Throughput (TPS): The system achieved an average throughput of 0.68 transactions per second under sharding, more than double the 0.26 tx/s observed in the non-sharded model.

Propagation Latency: Though less variable overall, propagation latency was consistently lower in sharded transactions, attributable to reduced queuing and lighter coordination requirements.

Scalability Patterns: As system load increased, sharded transactions exhibited flat or mildly rising execution curves, whereas non-sharded performance deteriorated in a near-linear manner, confirming the scalability bottleneck.

These results strongly support the architectural design decision to include sharding as a core concurrency strategy.

6.5 Performance Evaluation Summary

This evaluation confirms that sharding offers substantial benefits in managing blockchain concurrency and enhancing throughput. By distributing transactions across isolated shards, the system avoids global contention and enables:

Parallel execution without blocking,
Lower transaction latency,
Increased throughput and predictable scalability,
Reduced confirmation time,
Visual traceability for debugging and tuning.

Moreover, the integrated metrics dashboard is not only a benchmarking tool but also an educational visualisation environment. It provides developers and researchers with deep insight into transaction lifecycle behaviour, allowing real-time experimentation, performance tuning, and design validation through direct interaction with execution data.

7 Limitations

While this project successfully demonstrates sharded and non-sharded transaction execution in a simulated blockchain environment, several limitations exist that constrain the full applicability of the system:

No Consensus Mechanism: The current implementation does not incorporate a consensus algorithm such as PBFT or PoW, meaning block creation and validation are deterministic and controlled by a single backend process.

Single-Machine Simulation: The backend simulates shards and node behaviour locally within a controlled environment. Real-world scenarios involving distributed nodes across physical machines are not fully replicated.

Limited Fault Tolerance: Since there is no redundancy or fault recovery mechanism, any service crash would result in loss of transaction history or blockchain state.

Simplified Deadlock Model: Although the deadlock simulation feature allows circular wait conditions to be created manually, it does not include an automated deadlock detection and resolution mechanism.

Fixed Shard Assignment: The system does not currently support dynamic shard allocation or migration. Nodes must be manually assigned to shards through the UI.

Limited Smart Contract Support: Transactions only carry basic data payloads. There is no support for Turing complete smart contract logic or complex state transitions.

A Screenshots and UI Examples

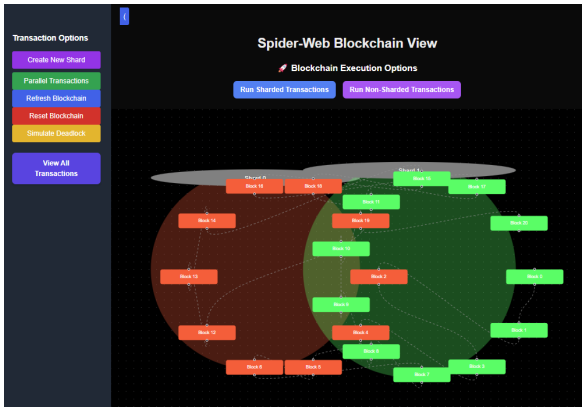

Figure 2: Spider-web Blockchain Visualisation showing **sharded** block groups and interconnections.

Figure 3: UI showing all recorded transactions with performance metrics.

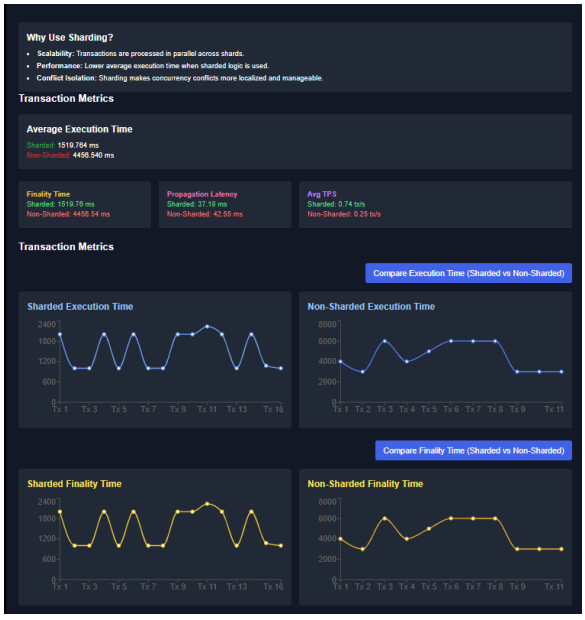

Figure 4: UI snapshot of real-time transaction activity and system response.

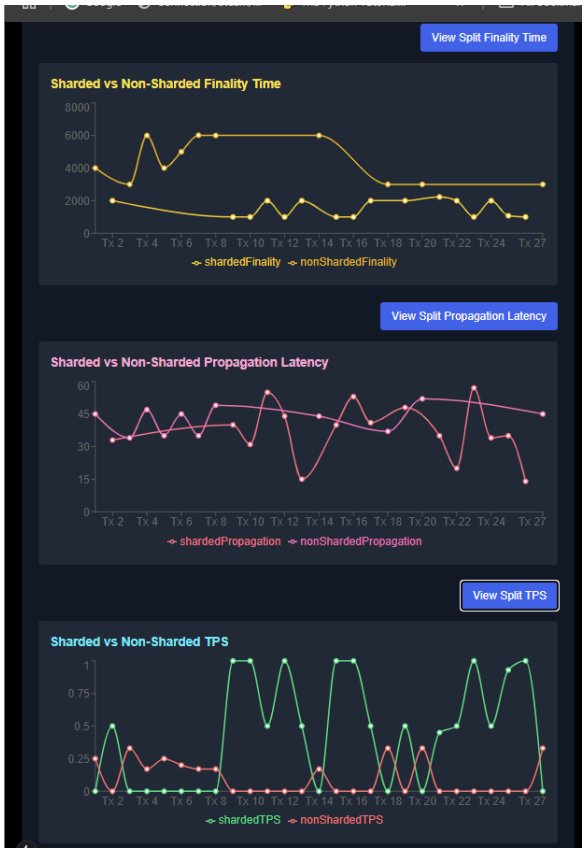

Figure 5: Combined metrics view showing execution trends.

Architecture Diagram

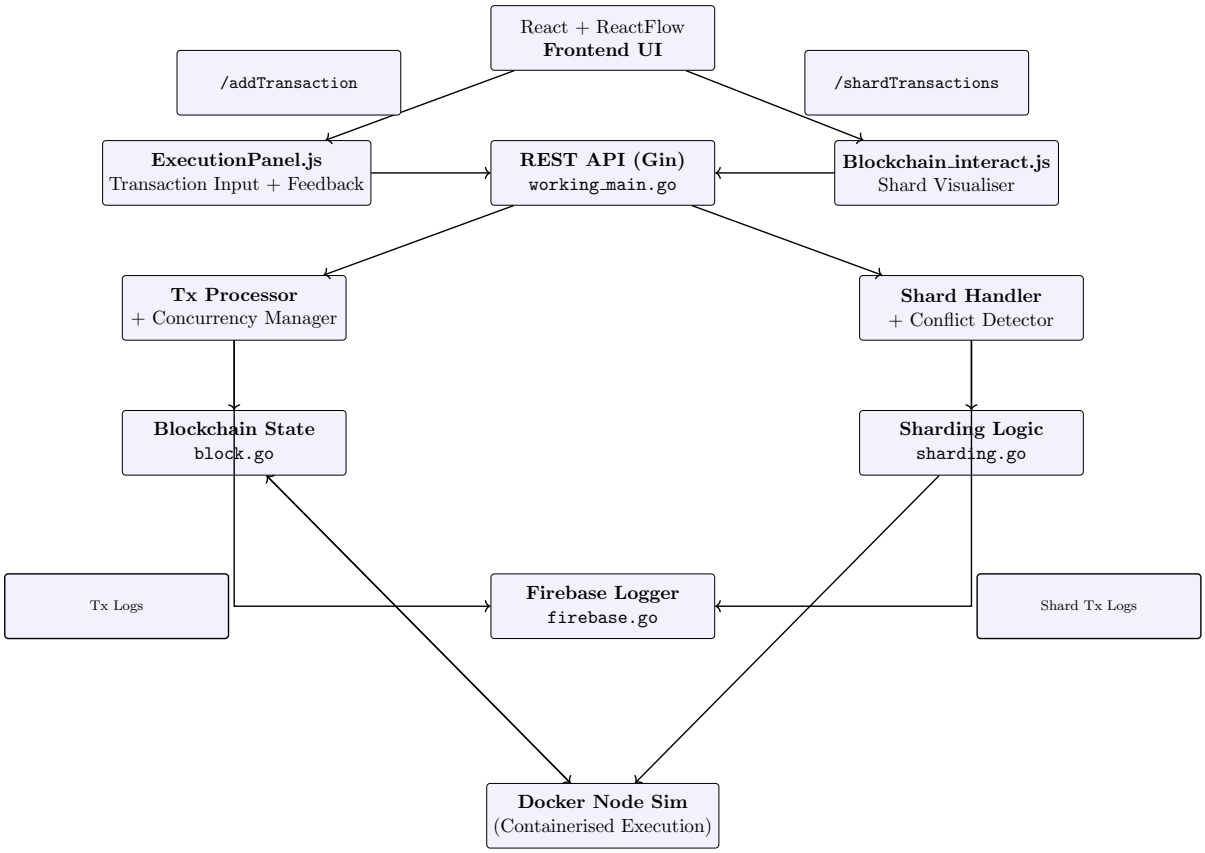

Figure 6: Expanded System Architecture for Blockchain Sharding Platform with React UI, Go Backend, Docker Simulation, and Firebase Logging

System Architecture Overview

Frontend (React + ReactFlow):
The user-facing interface is built using React for modular logic and ReactFlow for rendering dynamic blockchain graphs. Users interact via modals and execution panels to initiate transactions, simulate deadlocks, and inspect node states.
`ExecutionPanel.js` handles form input, validation, and feedback, while `Blockchain_interact.js` manages node layouts, visual feedback, and edge rendering.

REST API (Gin Framework):
The Go backend provides RESTful endpoints using the Gin web framework. Key routes include `/addTransaction`, `/shardTransactions`, and `/deadlocksim`, all defined in `working_main.go`. Middleware handles CORS, request parsing, and concurrency control.

Backend Logic (Golang):
Asynchronous execution is achieved using goroutines. Transactions are classified as sharded or non-sharded based on shard IDs, then processed independently. Deadlock simulations are triggered via pre-defined cyclic transactions between two nodes.

State Management (Blockchain and Sharding):
`block.go` defines blockchain data structures, linking blocks via hashes and maintaining transaction history. `sharding.go` manages shard assignments, supports static and dynamic strategies, and validates inter-shard routing logic.

Persistent Logging (Firebase Firestore):
`firebase.go` enables remote logging of transaction metadata (execution time, finality, TPS, type). It ensures log persistence using functions like `SaveTransactionToFirestore()` and `LoadTransactionsFromFirestore()` for UI state recovery and performance tracking.

Simulation Layer (Docker Integration):
Docker containers act as virtual nodes (or "blocks"). The backend interacts with Docker using its SDK, dynamically mapping container IDs to visualised nodes, enabling a sandboxed and distributed testing environment.

End-to-End System Flow:

1. User submits a transaction via the React UI (sharded or non-sharded).
2. Request is sent to the backend REST API for validation.
3. Backend executes the transaction via `processTransaction()` in a goroutine.
4. Block state (source and target) is updated in memory.
5. Metadata is logged to Firestore for persistence and dashboard metrics.
6. If Docker simulation is enabled, containers are queried and linked to the transaction context.
7. UI periodically polls the backend and updates visual state upon transaction completion.

Table 2: Key System Components and Responsibilities

Component	Description
`ExecutionPanel.js`	Captures user input, validation, and dispatches requests to backend.
`Blockchain_interact.js`	Visualises node and shard layout using ReactFlow.
`working_main.go`	Main backend router and entrypoint for API requests. Handles transaction processing.
`block.go`	Stores blockchain structure and handles linking of blocks and state updates.
`sharding.go`	Assigns shards, validates inter-shard routing, and detects conflicts.
`firebase.go`	Persists transaction logs to Firebase Firestore for metrics recovery.
`Docker API`	Used by backend to create/track containerised blocks in the simulation layer.

B API Reference

All endpoints communicate over HTTP using JSON. Each API returns a standard HTTP response code; errors are signalled with a 400+ status code and an **"error"** mes- sage in the body.

POST /addTransaction

Non-sharded transaction:

```
{"source":3,"target":5,"data":"Transfer","
    is_sharded":false}
```

POST /shardTransactions

Cross-shard batch:

```
{"transactions":[
{"source":[1],"target":[2],"data":"A->B"},
{"source":[3],"target":[5],"data":"B->D"}]
    }
```

GET /blockchain

Returns blockchain state:

- Block hashes
- Transactions
- Shard assignments

GET /transactionLogs

Returns:

- `TxID`, `source`, `target`
- `timestamp`, `status`

GET /transactionStatus/{txID}

Returns status: `pending`, `completed`, or `failed`

POST /assignNodesToShard

Dynamic reassignment:

```
{"shard_id":2,"nodes":[4,5,6]}
```

POST /deadlocksim

Simulates deadlock:

```
{"source":1,"target":2}
```

POST /resetBlockchain

Clears blockchain and resets to Shard 0.

GET /metrics/tps

Returns current TPS metric.

Appendicies

The following appendix includes links to the GitLab repository and setup instructions for deploying and testing the blockchain concurrency-confliction project.

Appendix A – GitLab / GitHub

Project Repository

This project can be accessed via:
GitLab (University-hosted): `https://gitlab.eeecs.qub.ac.uk/40295919/csc4006-project`
GitHub (Public mirror):
`https://github.com/ConnorM2020/Blockchain-Concurrency-Confliction-Resolution`

Project Overview

This project simulates transaction concurrency and deadlock behaviour in a blockchain system, supporting both sharded and non-sharded execution. It features:

A Go backend (RESTful API using Gin)
A React/Next.js frontend with ReactFlow for blockchain visualization
Docker-based simulation of block nodes

Firebase integration for persistent transaction logs
Hyperledger Fabric integration using Fablo for chaincode deployment

Key Features: Sharded/non-sharded transaction support
Cross-shard transaction execution
Parallel and deadlock transaction simulation
Execution time, finality, propagation latency, and TPS metrics

System Requirements

Backend (Go): Go 1.21+
Docker and Docker Compose
Frontend (Next.js/React): Node.js 18+
Tailwind CSS and Recharts

Blockchain Infrastructure: Fablo + Hyperledger Fabric 2.x
Fablo config path: `fablo-target/fabric-config`

Installation Guide

1. **Clone the repository:**

   ```
   git clone https://gitlab.eeecs.qub.ac.uk/40295919/csc4006-project.git
   cd csc4006-project
   ```

2. **Start Hyperledger Fabric (via Fablo):**

   ```
   cd fablo
   fablo reset   # if fabric-config folders exist
   fablo up
   ```

3. **Run Go Backend:**

   ```
   cd Blockchain_Codebase
   go build -o blockchain_app
   ./blockchain_app --server -process
   ```

4. **Run Frontend:**

```
cd frontend
npm install
npm run dev
```

Execution Examples

Sharded Transaction: Click "Run Sharded Transactions"
Non-Sharded Transaction: Click "Run Non-Sharded Transactions"
Deadlock Simulation: Open side panel → Simulate Deadlock
View Metrics: Click "View All Transactions" to access TPS, latency, execution time, and finality data

Replication Guide

1. Ensure **Docker** and **Node.js** are installed.
2. Launch **Fablo**: `fablo up`
3. Compile and run backend:
   `go build -o blockchain_app && ./blockchain_app --server -process`
4. Start frontend: `npm run dev`
5. Open browser at: `http://localhost:3000`
6. Use the interface to simulate various transaction types and deadlocks.

License

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A Conclusion and Future Work

This project demonstrated a modular, interactive simulation of a sharded blockchain architecture to address scalability and concurrency challenges in distributed ledgers. By combining front-end visualisation, backend coordination, and persistent logging, the platform provides a comprehensive environment to evaluate sharded versus non-sharded execution strategies.

Key Contributions

Built a **React + ReactFlow** front-end to visualise the blockchain state, enable dynamic shard assignment, and provide live transaction feedback.
Developed a **Go-based REST API** for transaction routing, execution, and logging across monolithic and sharded workflows.
Integrated **Firebase Firestore** for persistent logs, recovery,
and performance benchmarking.
Designed a **metrics dashboard** to visualise execution time, finality, latency, and TPS.
Added a **deadlock simulation mode** to highlight concurrency bottlenecks in non-sharded systems.

Impact and Validation

Empirical results confirm that sharding improves performance:

- **Execution and finality times** were reduced by over 50%.
- **Throughput (TPS)** increased under concurrent workloads, validating scalability.
- **Propagation latency** was slightly improved due to asynchronous shard processing.

These outcomes were presented via a real-time dashboard for accessible analysis of transaction behaviour and system load response.

Limitations and Challenges

- No decentralised consensus algorithm is implemented.
- Nodes are simulated locally; dynamic shard migration is unsupported.
- Smart contract execution and automated deadlock resolution remain unimplemented.

Future Work

- **Incorporate BFT-style consensus** (e.g., PBFT, Raft) for decentralised shard validation.
- **Enable dynamic shard reallocation** for real-time load balancing.
- **Deploy across distributed infrastructure** using orchestration tools like Kubernetes.
- **Add smart contract support** for programmable ledger operations.
- **Explore advanced concurrency control**, such as lock-free or CRDT-based methods.

Final Remarks

This work shows how sharding can evolve blockchain from a globally locked model to a high-throughput, distributed paradigm. The platform's modularity, empirical evaluation, and educational value lay the groundwork for future research and scalable blockchain development—bridging theory with practical feasibility.