Causally Consistent Distributed Key-Value Store using Vector Clocks

Assignment 1 – Fundamentals of Distributed Systems

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1. Introduction

Distributed systems face a major challenge in maintaining consistency across multiple nodes, especially when events happen concurrently. Traditional Lamport clocks can only establish a partial order, but they fall short in capturing causal relationships between events. To address this, this project implements Vector Clocks for tracking causality and ensures that a key-value store remains causally consistent across three nodes.

2. Objective

The goal of this assignment is to:
- Understand causal ordering in distributed systems.
- Implement a multi-node key-value store using Vector Clocks.
- Maintain causal consistency by buffering out-of-order writes.
- Test and verify the correctness using a controlled scenario.

3. Technologies Used

Tool	Purpose
Python (3.10)	Node logic, vector clock implementation
Flask	API server for each node
Docker	Containerizing each node
Docker Compose	Orchestrating all 3 nodes together
Requests lib	Used in client to send HTTP POST/GET

4. System Architecture

- Three independent nodes (X, Y, Z), each runs a Flask server and maintains:
  - A local key-value store
  - A Vector Clock
  - A message buffer for undeliverable updates
- Nodes communicate over HTTP and apply causal rules before accepting writes.
- Writes with missing dependencies are buffered and processed later.

5. Implementation Overview

➤ Vector Clock Logic:

Each node has a clock like {X: 0, Y: 0, Z: 0}.
On every write:
- It increments its own entry.
- Sends the entire clock with the update.
On receiving:
- It checks causal readiness using is_causally_ready().
- If not ready, it buffers the message.

➤ Node Logic (service_node.py):

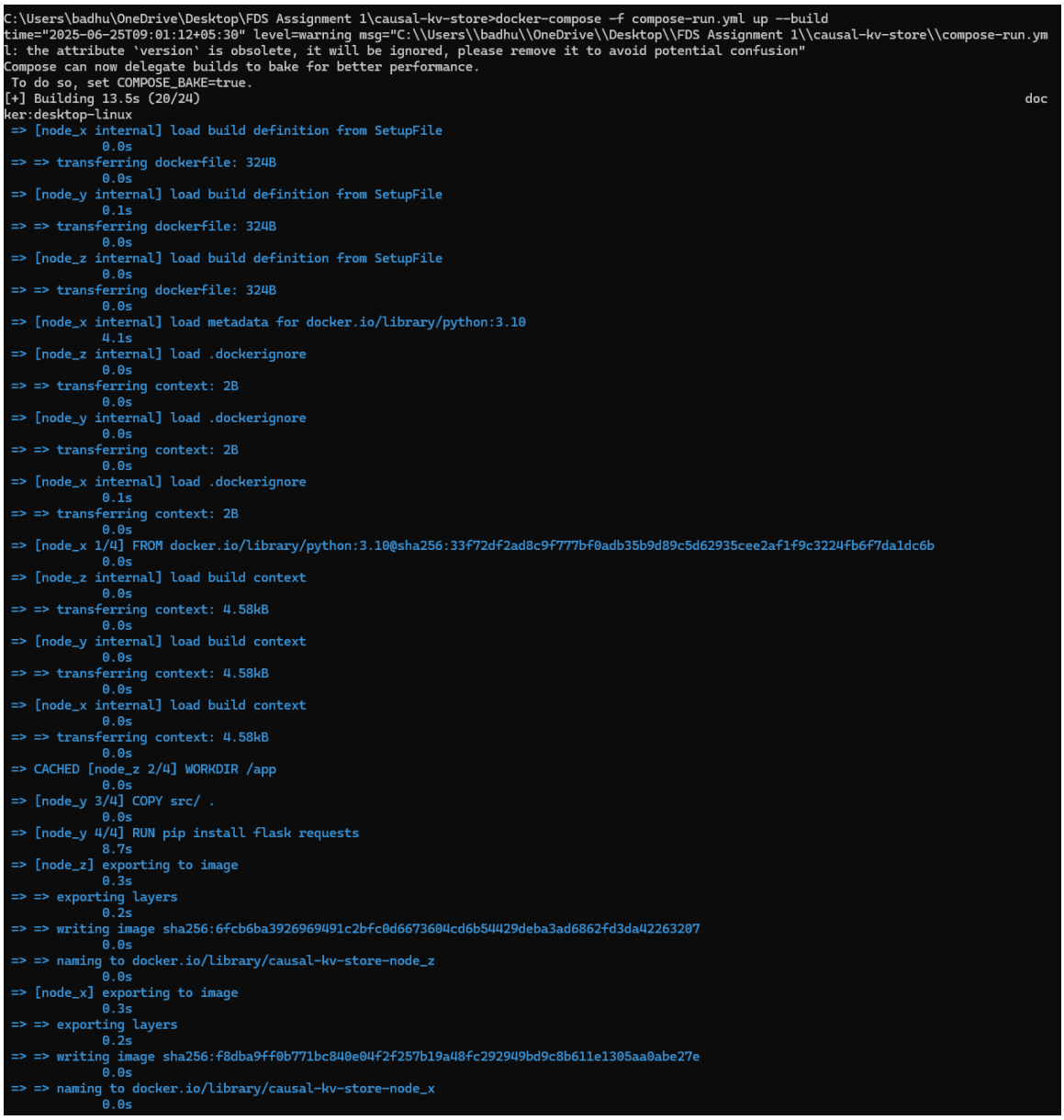
- Implements PUT endpoint to accept writes.
- Checks causal conditions.
- Starts a background thread to retry buffered writes.

➤ Dockerization:

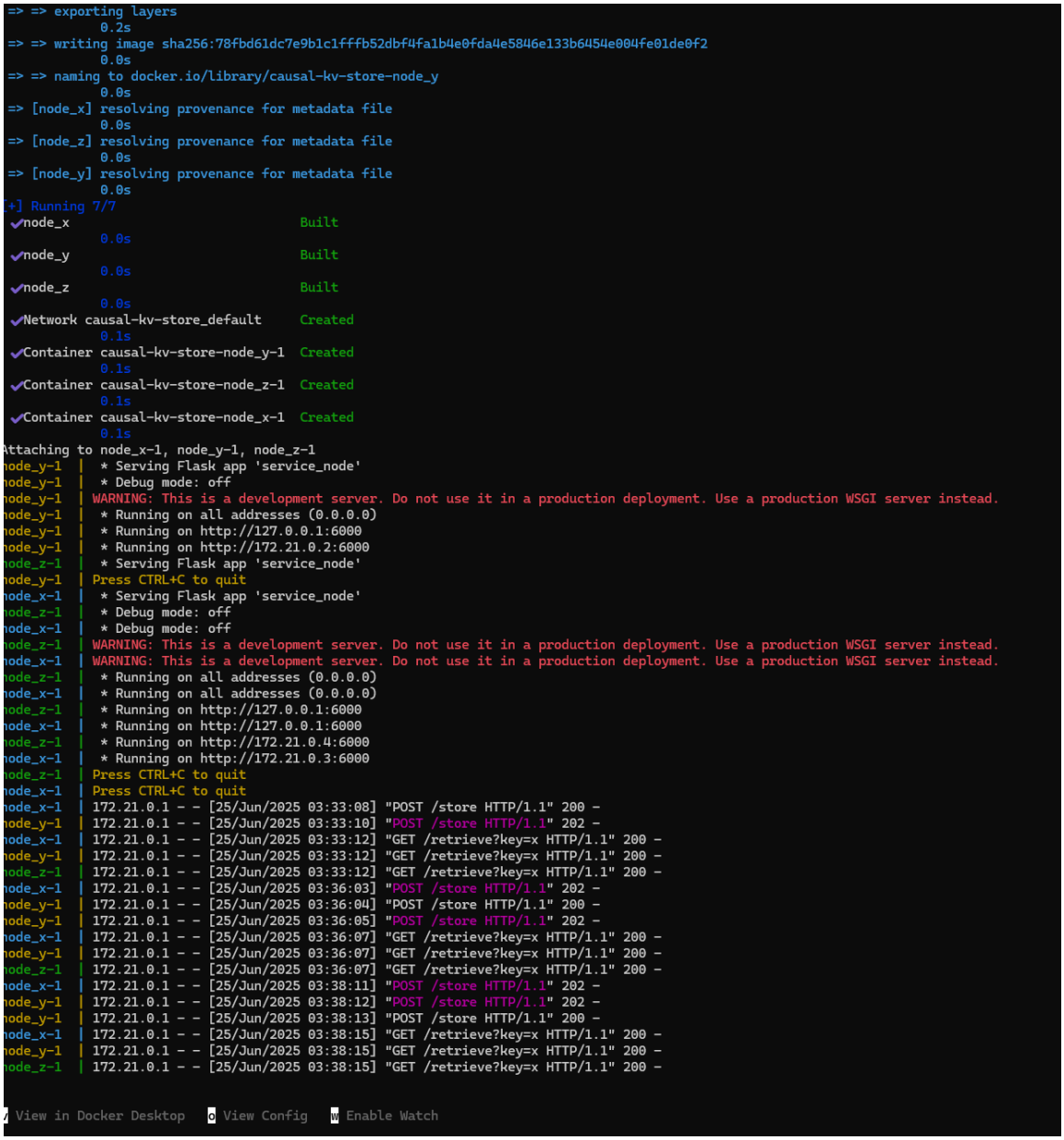
Each node is containerized using a custom Dockerfile, and launched via compose-run.yml.

6. Screenshots

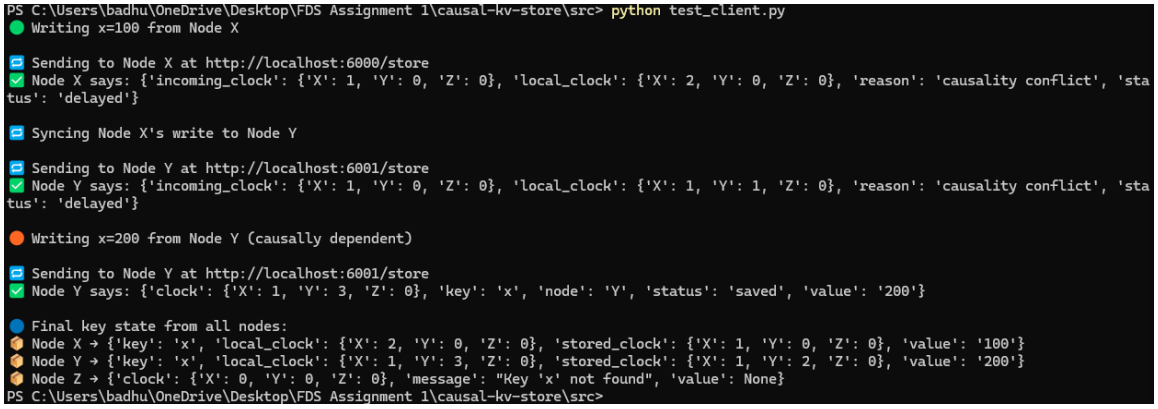
Screenshot 1 – System Build and Startup using Docker Compose



```
C:\Users\badhu\OneDrive\Desktop\FDS Assignment 1\causal-kv-store>docker-compose -f compose-run.yml up --build
time="2025-06-25T09:01:12+05:30" level=warning msg="C:\\Users\\badhu\\OneDrive\\Desktop\\FDS Assignment 1\\causal-kv-store\\compose-run.yml: the attribute `version` is obsolete, it will be ignored, please remove it to avoid potential confusion"
Compose can now delegate builds to bake for better performance.
 To do so, set COMPOSE_BAKE=true.
[+] Building 13.5s (20/24)                                                                                                  docker:desktop-linux
 => [node_x internal] load build definition from SetupFile                                                                            0.0s
 => => transferring dockerfile: 324B                                                                                                  0.0s
 => [node_y internal] load build definition from SetupFile                                                                            0.1s
 => => transferring dockerfile: 324B                                                                                                  0.0s
 => [node_z internal] load build definition from SetupFile                                                                            0.0s
 => => transferring dockerfile: 324B                                                                                                  0.0s
 => [node_x internal] load metadata for docker.io/library/python:3.10                                                                 4.1s
 => [node_z internal] load .dockerignore                                                                                              0.0s
 => => transferring context: 2B                                                                                                       0.0s
 => [node_y internal] load .dockerignore                                                                                              0.0s
 => => transferring context: 2B                                                                                                       0.0s
 => [node_x internal] load .dockerignore                                                                                              0.1s
 => => transferring context: 2B                                                                                                       0.0s
 => [node_x 1/4] FROM docker.io/library/python:3.10@sha256:33f72df2ad8c9f777bf0adb35b9d89c5d62935cee2af1f9c3224fb6f7da1dc6b           0.0s
 => [node_z internal] load build context                                                                                              0.0s
 => => transferring context: 4.58kB                                                                                                   0.0s
 => [node_y internal] load build context                                                                                              0.0s
 => => transferring context: 4.58kB                                                                                                   0.0s
 => [node_x internal] load build context                                                                                              0.0s
 => => transferring context: 4.58kB                                                                                                   0.0s
 => CACHED [node_z 2/4] WORKDIR /app                                                                                                  0.0s
 => [node_y 3/4] COPY src/ .                                                                                                          0.0s
 => [node_y 4/4] RUN pip install flask requests                                                                                       8.7s
 => [node_z] exporting to image                                                                                                       0.3s
 => => exporting layers                                                                                                               0.2s
 => => writing image sha256:6fcb6ba3926969491c2bfc0d6673604cd6b54429deba3ad6862fd3da42263207                                          0.0s
 => => naming to docker.io/library/causal-kv-store-node_z                                                                             0.0s
 => [node_x] exporting to image                                                                                                       0.3s
 => => exporting layers                                                                                                               0.2s
 => => writing image sha256:f8dba9ff0b771bc840e04f2f257b19a48fc292949bd9c8b611e1305aa0abe27e                                          0.0s
 => => naming to docker.io/library/causal-kv-store-node_x                                                                             0.0s
```



📸 Screenshot 2 – Client Test Output & Causal Consistency



7. Observations

- When Node Y attempts a write dependent on Node X's earlier write, it gets buffered until Node X's update is applied.
- All final values are consistent once causal order is respected.
- Demonstrated that messages arriving out of order are safely handled and applied in correct order.

8. Challenges Faced

- Docker Desktop didn't start initially — solved by rebooting and running as administrator.
- Buffer logic and is_causally_ready() conditions needed several test runs to get right.
- Port forwarding in docker-compose.yml required precise configuration for testing.

9. Learnings

- Gained deep understanding of causal ordering vs total ordering.
- Learned to write and test vector clocks from scratch.
- Understood how to containerize distributed applications.
- Practiced real-world debugging in Docker environments.

10. Demo Video Link (Max 3 Minutes)

Video Link:
https://drive.google.com/file/d/1TpY0GuT9O97JrcOD1dShu-9ipUCPlDfs/view?usp=sharing

☑ File Structure Followed

```
causal-kv-store/
│
├── src/
│   ├── service_node.py
│   ├── causal_clock.py
│   └── test_client.py
│
├── SetupFile (Dockerfile)
├── compose-run.yml
└── project_report.pdf
```