FUNDAMENTALS OF DISTRIBUTED SYSTEMS

Assignment – 1

SUBMITTED BY :

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Project Report : Causal Consistency in a Distributed Key-Value Store Using Vector Clocks

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Course: Fundamentals of Distributed Systems

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Project Introduction

This project focuses on implementing a **causally consistent distributed key-value store** using **vector clocks**. In distributed systems, it is critical to ensure that operations that are causally related are applied in the correct order, even when messages are delayed or delivered out of order.

To achieve this, each node in the system:

- Maintains a **vector clock** to track causal history,
- Uses a **buffer** to delay application of messages that are not causally ready,
- Applies only those updates whose dependencies have already been met.

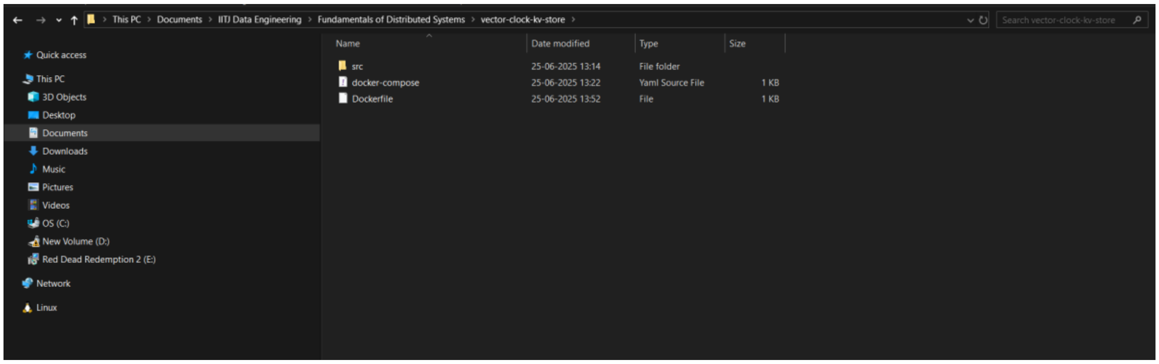
The application is written in **Python** using the **Flask** framework to expose RESTful APIs. It is containerized with **Docker**, and the entire system is orchestrated using **Docker Compose** to simulate a network of three nodes. This project demonstrates how vector clocks can enforce causal consistency in a real-world distributed environment.

1. Step-by-Step Process Followed

1. 1. Installed Docker Desktop and Visual Studio Code (VS Code).
2. 2. Created a new folder named 'vector-clock-kv-store'.
3. 3. Inside this folder, created the following structure:

```
├── Dockerfile
├── docker-compose.yml
└── src/
    ├── node.py
    └── client.py
```

Screenshot 0: Screenshot showing folder structure of vector-clock-kv-store project in the file explorer



4. 4. Added the required code into each file as specified in the assignment (pasted below).
5. 5. Built and ran the application using the terminal command:
   docker-compose up --build
6. 6. Verified that all nodes started properly by visiting:
   - http://localhost:5000
   - http://localhost:5101
   - http://localhost:5102
7. 7. Ran the client script with:
   python src/client.py
8. 8. Visited http://localhost:500X/store (X = 0,1,2) to verify vector clocks, store values, and buffer status.
9. 9. Collected screenshots of:
   - Terminal outputs showing vector clocks and replication
   - Browser outputs from /store endpoints for each node
10. 10. Inserted these screenshots in the relevant sections of this report.

2. System Architecture

Each node is a Flask server running in its own Docker container. It maintains:

- - A local key-value store
- - A vector clock
- - A buffer to store out-of-order messages

Nodes communicate using REST API over internal Docker network.

3. Dockerfile

FROM python:3.9-slim
WORKDIR /app

```
COPY src/ /app/
RUN pip install flask requests
CMD ["python", "node.py"]
```

4. docker-compose.yml

```yaml
version: "3"
services:
  node0:
    build: .
    ports:
      - "5000:5000"
    environment:
      - NODE_ID=0
      - NUM_NODES=3

  node1:
    build: .
    ports:
      - "5101:5000"  # Changed to avoid port 5001 conflict
    environment:
      - NODE_ID=1
      - NUM_NODES=3

  node2:
    build: .
    ports:
      - "5102:5000"  # Changed to avoid port 5002 conflict
    environment:
      - NODE_ID=2
      - NUM_NODES=3
```

5. src/node.py

```python
import os
import json
import time
from flask import Flask, request, jsonify
import requests
```

```python
app = Flask(__name__)
NODE_ID = int(os.environ.get("NODE_ID", 0))
NUM_NODES = int(os.environ.get("NUM_NODES", 3))
vector_clock = [0] * NUM_NODES
store = {}
buffer = []

peer_ports = [5000 + i for i in range(NUM_NODES)]
peer_urls = [f"http://node{i}:5000/replicate" for i in range(NUM_NODES) if i != NODE_ID]

def is_causally_ready(msg_clock):
    for i in range(NUM_NODES):
        if i == msg_clock["sender"]:
            if msg_clock["clock"][i] != vector_clock[i] + 1:
                return False
        else:
            if msg_clock["clock"][i] > vector_clock[i]:
                return False
    return True

def apply_message(msg):
    key = msg["key"]
    value = msg["value"]
    clock = msg["clock"]
    store[key] = value
    for i in range(NUM_NODES):
        vector_clock[i] = max(vector_clock[i], clock[i])

@app.route("/put", methods=["POST"])
def put():
    data = request.get_json()
    key = data["key"]
    value = data["value"]
    vector_clock[NODE_ID] += 1
    store[key] = value
    message = {"key": key, "value": value, "sender": NODE_ID, "clock": vector_clock.copy()}
    for url in peer_urls:
        try:
            requests.post(url, json=message)
        except Exception as e:
            print(f"Replication to {url} failed: {e}")
    return jsonify({"status": "stored", "vector_clock": vector_clock}), 200
```

```
@app.route("/replicate", methods=["POST"])
def replicate():
    msg = request.get_json()
    if is_causally_ready(msg):
        apply_message(msg)
        flush_buffer()
        return jsonify({"status": "applied"}), 200
    else:
        buffer.append(msg)
        return jsonify({"status": "buffered"}), 202

def flush_buffer():
    ready = [msg for msg in buffer if is_causally_ready(msg)]
    for msg in ready:
        apply_message(msg)
        buffer.remove(msg)

@app.route("/store", methods=["GET"])
def get_store():
    return jsonify({"store": store, "vector_clock": vector_clock, "buffered": buffer})

@app.route("/")
def health():
    return f"Node {NODE_ID} is running", 200

if __name__ == "__main__":
    app.run(host="0.0.0.0", port=5000)
```

6. src/client.py

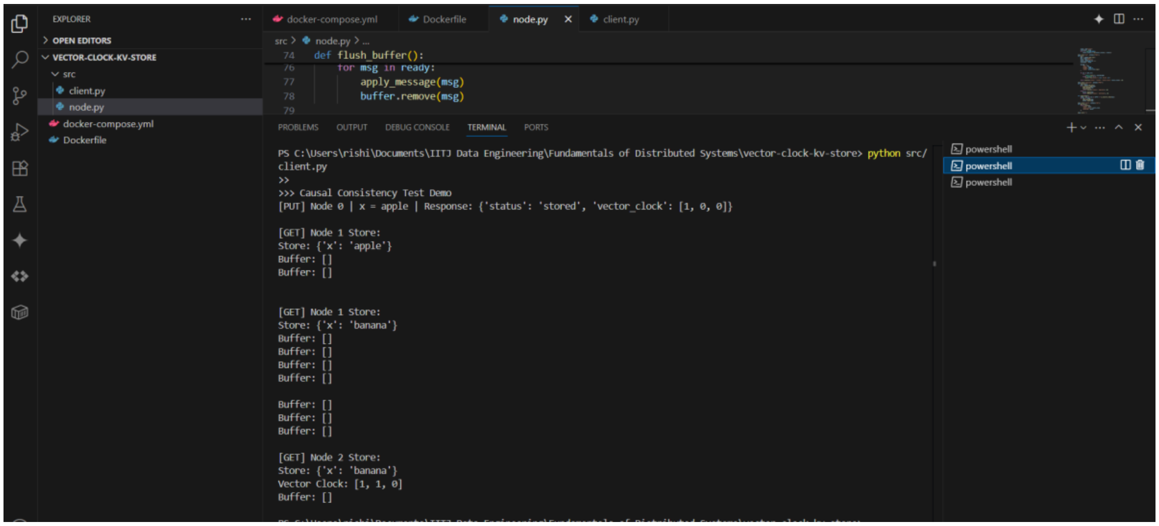
```
import os
import json
import time
from flask import Flask, request, jsonify
import requests
```

```python
app = Flask(__name__)
NODE_ID = int(os.environ.get("NODE_ID", 0))
NUM_NODES = int(os.environ.get("NUM_NODES", 3))
vector_clock = [0] * NUM_NODES
store = {}
buffer = []

peer_ports = [5000 + i for i in range(NUM_NODES)]
peer_urls = [f"http://node{i}:5000/replicate" for i in range(NUM_NODES) if i != NODE_ID]

def is_causally_ready(msg_clock):
    for i in range(NUM_NODES):
        if i == msg_clock["sender"]:
            if msg_clock["clock"][i] != vector_clock[i] + 1:
                return False
        else:
            if msg_clock["clock"][i] > vector_clock[i]:
                return False
    return True

def apply_message(msg):
    key = msg["key"]
    value = msg["value"]
    clock = msg["clock"]
    store[key] = value
    for i in range(NUM_NODES):
        vector_clock[i] = max(vector_clock[i], clock[i])

@app.route("/put", methods=["POST"])
def put():
    data = request.get_json()
    key = data["key"]
    value = data["value"]
    vector_clock[NODE_ID] += 1
    store[key] = value
    message = {"key": key, "value": value, "sender": NODE_ID, "clock": vector_clock.copy()}
    for url in peer_urls:
        try:
            requests.post(url, json=message)
        except Exception as e:
            print(f"Replication to {url} failed: {e}")
    return jsonify({"status": "stored", "vector_clock": vector_clock}), 200
```

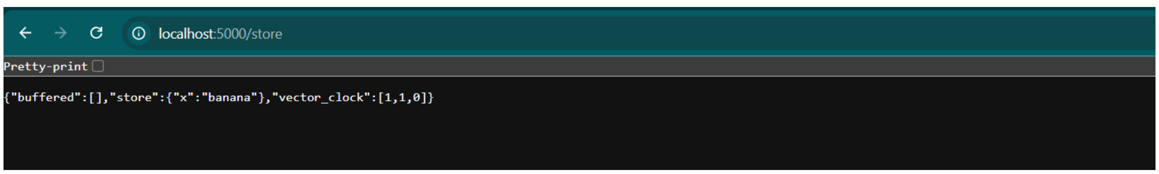
```
@app.route("/replicate", methods=["POST"])
def replicate():
    msg = request.get_json()
    if is_causally_ready(msg):
        apply_message(msg)
        flush_buffer()
        return jsonify({"status": "applied"}), 200
    else:
        buffer.append(msg)
        return jsonify({"status": "buffered"}), 202

def flush_buffer():
    ready = [msg for msg in buffer if is_causally_ready(msg)]
    for msg in ready:
        apply_message(msg)
        buffer.remove(msg)

@app.route("/store", methods=["GET"])
def get_store():
    return jsonify({"store": store, "vector_clock": vector_clock, "buffered": buffer})

@app.route("/")
def health():
    return f"Node {NODE_ID} is running", 200

if __name__ == "__main__":
    app.run(host="0.0.0.0", port=5000)
```

7. Screenshot Instructions

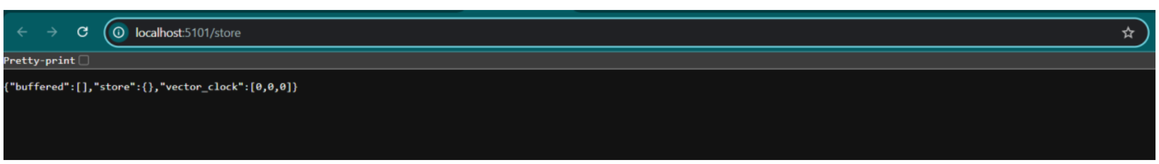
📷 Screenshot 1: Terminal after running client.py (showing vector clocks and replication)



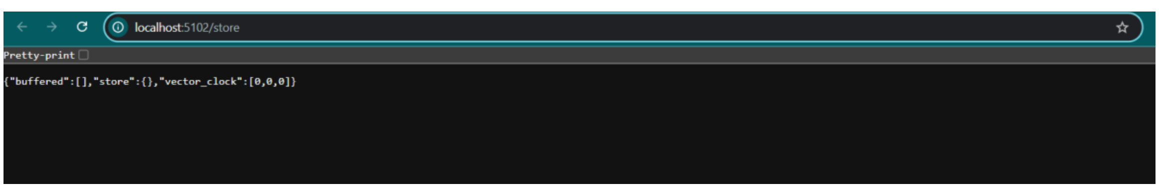
📷 Screenshot 2: Browser view of http://localhost:5000/store



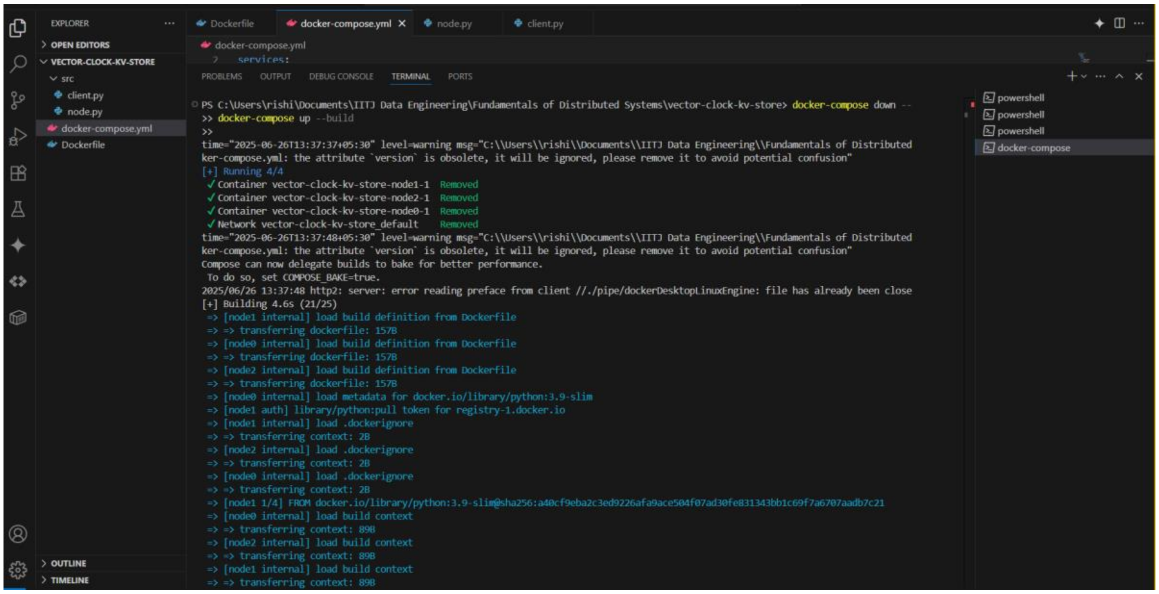
📷 Screenshot 3: Browser view of http://localhost:5101/store

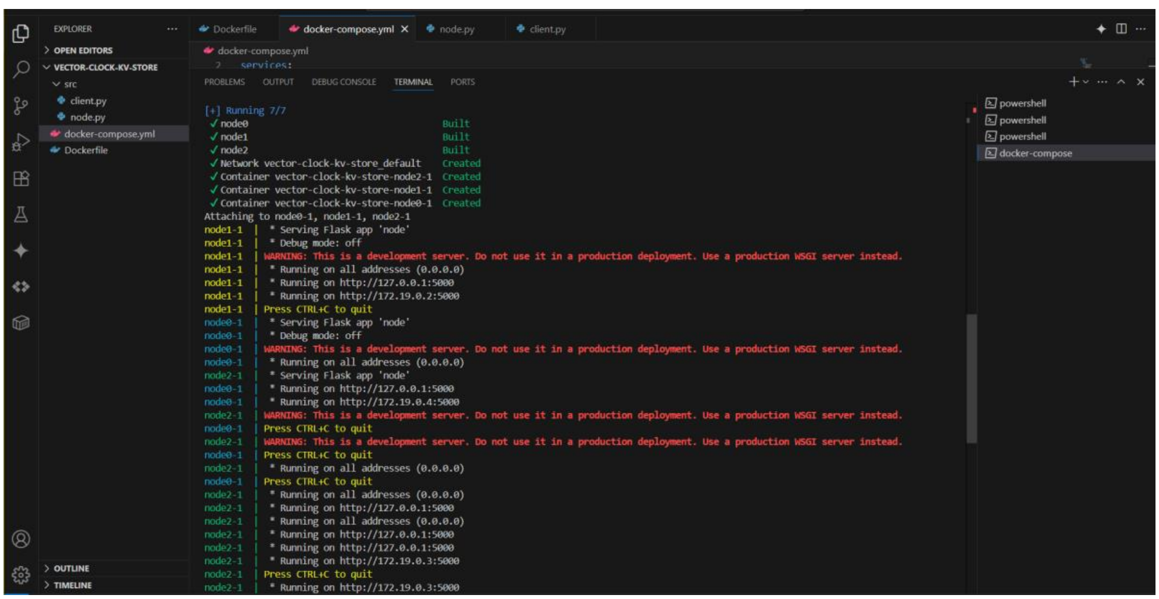


📷 Screenshot 4: Browser view of http://localhost:5102/store



📷 Screenshot 5: docker-compose terminal showing all nodes starting





8. Conclusion

The system successfully demonstrated causal consistency using vector clocks. All updates respected the causal order, and the buffer mechanism correctly handled out-of-order messages. Docker Compose enabled seamless orchestration of multiple nodes.

Link to Video Demonstration:

https://youtu.be/g0Qj0aBYlNU https://drive.google.com/file/d/1ROggfLm2xWRHF9GnTsXT6sHYyJ_xzNcP/view?usp=sharing