Causally Consistent Key-Value Store using Vector Clocks

Project Report
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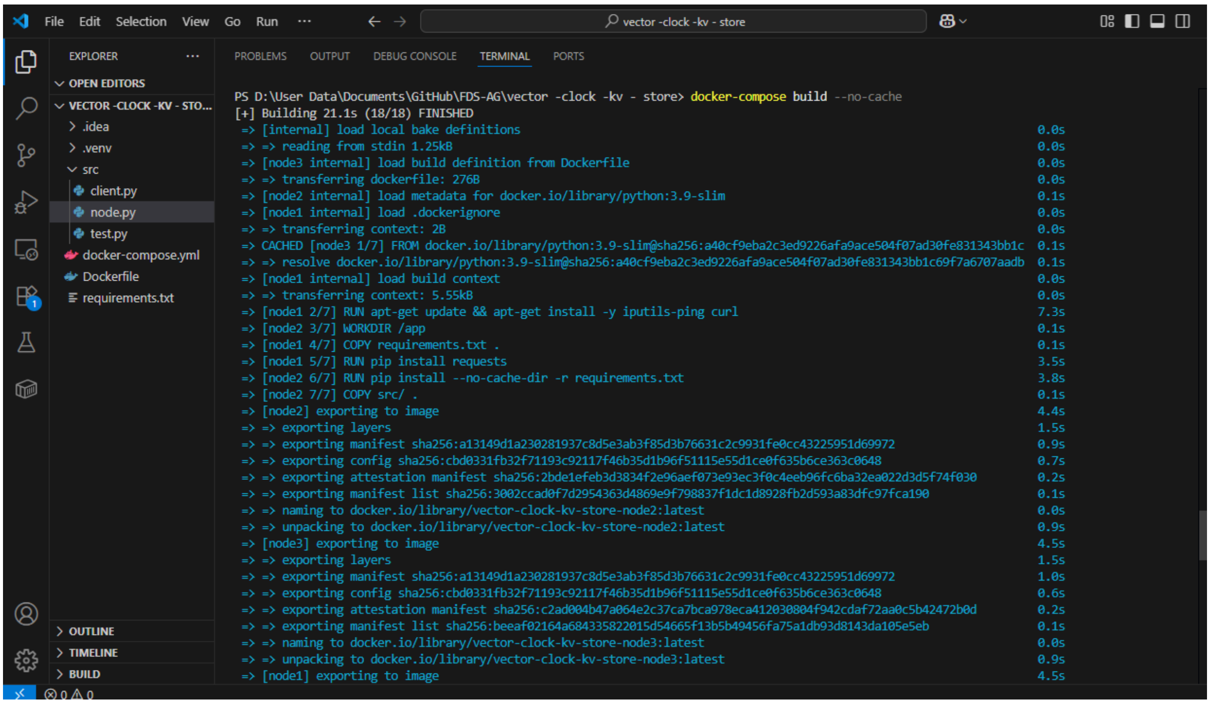
1 Objective

To implement a distributed, multi-node key-value store that ensures **causal consistency** by using **Vector Clocks** to track the causal relationship between events across nodes.

2 Architecture Overview

2.1 System Components

- **Nodes:** Independent Flask-based services representing key-value store instances. Each node maintains:
    - A **local vector clock**
    - A **local key-value store**
    - A **replication buffer** for causality-enforcing message delivery
- **Client:** A Python script to simulate operations and validate causal consistency across nodes
- **Docker Compose:** Used to containerize and orchestrate the three-node system



- **3 nodes created**

```
PROBLEMS    OUTPUT    DEBUG CONSOLE    TERMINAL    PORTS

 => => exporting layers                                                                              1.5s
 => => exporting manifest sha256:a13149d1a230281937c8d5e3ab3f85d3b76631c2c9931fe0cc43225951d69972   0.9s
 => => exporting config sha256:cbd0331fb32f71193c92117f46b35d1b96f51115e55d1ce0f635b6ce363c0648     0.7s
 => => exporting attestation manifest sha256:b47ca13385b968d6b33d3cbe3be06ad4352d30888e848fd6eeab6680dc9c090e  0.2s
 => => exporting manifest list sha256:b993ec40a32e4893cb58053e7354b590fc5551f10da0a7ef11e30ba11614f3bd  0.1s
 => => naming to docker.io/library/vector-clock-kv-store-node1:latest                               0.0s
 => => unpacking to docker.io/library/vector-clock-kv-store-node1:latest                            0.9s
 => [node2] resolving provenance for metadata file                                                  0.1s
 => [node1] resolving provenance for metadata file                                                  0.1s
 => [node3] resolving provenance for metadata file                                                  0.0s
[+] Building 3/3
 ✓ node3  Built                                                                                      0.0s
 ✓ node1  Built                                                                                      0.0s
 ✓ node2  Built                                                                                      0.0s
PS D:\User Data\Documents\GitHub\FDS-AG\vector -clock -kv - store> docker-compose up -d
[+] Running 4/4
 ✓ Network kvstore_network  Created                                                                  0.0s
 ✓ Container node2          Started                                                                  0.7s
 ✓ Container node3          Started                                                                  0.9s
 ✓ Container node1          Started                                                                  0.9s
PS D:\User Data\Documents\GitHub\FDS-AG\vector -clock -kv - store> docker-compose ps
NAME     IMAGE                       COMMAND            SERVICE   CREATED         STATUS         PORTS
node1    vector-clock-kv-store-node1   "python node.py"   node1     4 seconds ago   Up 3 seconds   0.0.0.0:5001->5000/tcp, [::]:5001->5000/t
cp
node2    vector-clock-kv-store-node2   "python node.py"   node2     4 seconds ago   Up 3 seconds   0.0.0.0:5002->5000/tcp, [::]:5002->5000/t
cp
node3    vector-clock-kv-store-node3   "python node.py"   node3     4 seconds ago   Up 3 seconds   0.0.0.0:5003->5000/tcp, [::]:5003->5000/t
cp
```

2.2 Key Features

- Nodes replicate updates to all other nodes using HTTP POST.
- Vector clocks are sent along with every replicated write.
- Each node uses the **Causal Delivery Rule** to determine whether an update can be immediately applied or should be buffered.

Vector Clock Rules:

- On a local write: increment the node's clock.
- On receive: compare vector clock to decide if causal dependencies are met.
- Buffer updates if causal dependencies are not yet satisfied.

3 Implementation Details

3.1 Vector Clock Logic

- Each node tracks a dictionary-based vector clock (e.g., {"node1": 1, "node2": 0, "node3": 0}).
    - **On local write**: Increment own clock
    - **On receiving a write**: Merge clocks and check causality

3.2 Node Operations

- /write: Handles client writes (increments clock, replicates)

- /receive: Processes replicated writes (checks causality, buffers if needed)
- /read: Returns key-value pair with latest clock

3.3 Causal Consistency Rules

- A write is applied only if:
    - All preceding operations (per vector clock) have been processed
    - Otherwise, it is buffered and retried later

4 Test Scenario & Verification

4.1 Causal Consistency Test

Using client.py, the following scenario is executed:

1. Write x=5 to node1

```
PROBLEMS    OUTPUT    DEBUG CONSOLE    TERMINAL    PORTS

node1  |  * Running on http://172.20.0.3:5000
node1  | Press CTRL+C to quit
node1  | 172.20.0.1 - - [23/Jun/2025 07:57:29] "GET /health HTTP/1.1" 200 -
node1  |
node1  | [node1] Received write request
node1  | [node1] Write: x=5, clock={'node1': 1, 'node2': 0, 'node3': 0}
node1  | [node1] Replicating to http://node2:5000/receive key=x, value=5
node1  | 172.20.0.1 - - [23/Jun/2025 07:57:29] "POST /write HTTP/1.1" 200 -
node1  | [node1] Replicating to http://node3:5000/receive key=x, value=5
node1  |
node1  | 172.20.0.2 - - [23/Jun/2025 07:57:30] "POST /receive HTTP/1.1" 200 -
node1  | [node1] Received replication: {'key': 'x', 'value': 10, 'sender': 'node2', 'timestamp': {'node1': 1, 'node2': 1, 'node3':
 0}}
node1  | [node1] Applied replication: x=10, clock={'node1': 1, 'node2': 1, 'node3': 0}
PS D:\User Data\Documents\GitHub\FDS-AG\vector -clock -kv - store>
```

2. **Read x from node2**, capturing its vector clock

```
PROBLEMS    OUTPUT    DEBUG CONSOLE    TERMINAL    PORTS

node2  | 172.20.0.1 - - [23/Jun/2025 07:57:29] "GET /health HTTP/1.1" 200 -
node2  |
node2  | [node2] Received replication: {'key': 'x', 'value': 5, 'sender': 'node1', 'timestamp': {'node1': 1, 'node2': 0, 'node3':
0}}
node2  | [node2] Applied replication: x=5, clock={'node1': 1, 'node2': 0, 'node3': 0}
node2  | 172.20.0.3 - - [23/Jun/2025 07:57:29] "POST /receive HTTP/1.1" 200 -
node2  | 172.20.0.1 - - [23/Jun/2025 07:57:30] "GET /read?key=x HTTP/1.1" 200 -
node2  |
```

3. **Update x=10 on node2**, using the clock from step 2 as causal context

```
node2  | [node2] Received write request
node2  | [node2] Merged context from client: {'node1': 1, 'node2': 0, 'node3': 0}
node2  | [node2] Write: x=10, clock={'node1': 1, 'node2': 1, 'node3': 0}
node2  | [node2] Replicating to http://node1:5000/receive key=x, value=10
node2  | 172.20.0.1 - - [23/Jun/2025 07:57:30] "POST /write HTTP/1.1" 200 -
node2  | [node2] Replicating to http://node3:5000/receive key=x, value=10
PS D:\User Data\Documents\GitHub\FDS-AG\vector -clock -kv - store>
```

4. **Read from node3** to validate that x=10 is seen only after x=5 is processed

```
node3  |
node3  | [node3] Received replication: {'key': 'x', 'value': 5, 'sender': 'node1', 'timestamp': {'node1': 1, 'node2': 0, 'node3':
0}}
node3  | [node3] Applied replication: x=5, clock={'node1': 1, 'node2': 0, 'node3': 0}
node3  | 172.20.0.3 - - [23/Jun/2025 07:57:29] "POST /receive HTTP/1.1" 200 -
node3  |
node3  | [node3] Received replication: {'key': 'x', 'value': 10, 'sender': 'node2', 'timestamp': {'node1': 1, 'node2': 1, 'node3':
 0}}
node3  | [node3] Applied replication: x=10, clock={'node1': 1, 'node2': 1, 'node3': 0}
node3  | 172.20.0.2 - - [23/Jun/2025 07:57:30] "POST /receive HTTP/1.1" 200 -
node3  | 172.20.0.1 - - [23/Jun/2025 07:57:31] "GET /read?key=x HTTP/1.1" 200 -
PS D:\User Data\Documents\GitHub\FDS-AG\vector -clock -kv - store>
```

4.2 Out of Order Delivery Test

1. x=100 is written to node1 and artificially delayed in delivery to node3
2. Meanwhile, x=200 is written to node2 using the vector clock of the delayed message
3. node3 receives x=200 first, buffers it
4. Later, x=100 arrives, allowing x=200 to be applied correctly

```
node3  | [node3] Received replication: {'key': 'x', 'value': 200, 'sender': 'node2', 'timestamp': {'node1': 2, 'n
node3  | [node3] Cannot deliver yet, buffering...
node3  | 172.20.0.3 - - [23/Jun/2025 08:28:22] "POST /receive HTTP/1.1" 200 -
node3  |
node3  | [node3] Received replication: {'key': 'x', 'value': 100, 'sender': 'node1', 'timestamp': {'node1': 2, 'n
node3  | [node3] Applied replication: x=100, clock={'node1': 2, 'node2': 1, 'node3': 0}
node3  | 172.20.0.2 - - [23/Jun/2025 08:28:24] "POST /receive HTTP/1.1" 200 -
node3  | [node3] Applied replication: x=200, clock={'node1': 2, 'node2': 2, 'node3': 0}
node3  | 172.20.0.1 - - [23/Jun/2025 08:28:25] "GET /read?key=x HTTP/1.1" 200 -
```

```
=== Testing Out-of-Order Delivery Handling ===
Writing x=100 to node1...
Write successful. Clock: {'node1': 2, 'node2': 1, 'node3': 0}
Reading from node2...
Read value: 100 | Clock: {'node1': 2, 'node2': 1, 'node3': 0}
Updating to x=200 at node2...
Update successful. Clock: {'node1': 2, 'node2': 2, 'node3': 0}
Final value at node3: 200 | Clock: {'node1': 2, 'node2': 2, 'node3': 0}
✓ Out-of-order delivery handled correctly

🚀 All tests passed!
PS D:\User Data\Documents\GitHub\FDS-AG\vector -clock -kv - store>
```

Console Output

```
PS D:\User Data\Documents\GitHub\FDS-AG\vector -clock -kv - store> py src/client.py
Checking node availability...
✓ node1 ready | Clock: {'node1': 0, 'node2': 0, 'node3': 0}
✓ node2 ready | Clock: {'node1': 0, 'node2': 0, 'node3': 0}
✓ node3 ready | Clock: {'node1': 0, 'node2': 0, 'node3': 0}

=== Testing Causal Consistency ===
Writing x=5 to node1...
Write successful. Clock: {'node1': 1, 'node2': 0, 'node3': 0}
Reading from node2...
Read value: 5 | Clock: {'node1': 1, 'node2': 0, 'node3': 0}
Updating to x=10 at node2...
Update successful. Clock: {'node1': 1, 'node2': 1, 'node3': 0}
Final value at node3: 10 | Clock: {'node1': 1, 'node2': 1, 'node3': 0}
✓ Causal consistency verified

=== Testing Out-of-Order Delivery Handling ===
Writing x=100 to node1...
Write successful. Clock: {'node1': 2, 'node2': 1, 'node3': 0}
Reading from node2...
Read value: 100 | Clock: {'node1': 2, 'node2': 1, 'node3': 0}
Updating to x=200 at node2...
Update successful. Clock: {'node1': 2, 'node2': 2, 'node3': 0}
Final value at node3: 200 | Clock: {'node1': 2, 'node2': 2, 'node3': 0}
✓ Out-of-order delivery handled correctly

🚀 All tests passed!
PS D:\User Data\Documents\GitHub\FDS-AG\vector -clock -kv - store>
```

5. Conclusion

The project successfully implements causal consistency using vector clocks. Logs and output prove that:

- Nodes do not apply dependent writes until prior causal operations are received.
- Vector clocks are correctly merged and incremented.
- Buffered messages are correctly applied once causal constraints are met.

A demo video captures the architecture, operations, and both test cases

Folder structure in Github