Practical Byzantine Fault Tolerance Consensus and A Simple Distributed Ledger Application

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Abstract
Along with cryptocurrencies become a great success known to the world, how to deploy a large scale, robust Byzantine Fault Tolerant system turns into an interesting challenge in the technical community. We as a group of practitioners in distributed system are implementing the core consensus used in the distributed ledger – Practical Byzantine Fault Tolerance (known as PBFT, in Liskov), and designing a simple distributed ledger application of simulating the peer-to-peer transactions, in order to have a principle understanding the PBFT protocol, and its powerful strength to survive various software errors and malicious attacks.

1. Introduction

The objective of Byzantine fault tolerance is to be able to defend against Byzantine failures, in which components of a system fail with symptoms that prevent some components of the system from reaching agreement among themselves, where such agreement is needed for the correct operation of the system. Correctly functioning components of a Byzantine fault tolerant system will be able to provide the system's service, assuming there are not too many faulty components.
The application basically simulates the account transactions (deposit, withdraw, move, etc) of the bank system, which is distributed with data replicated. During the process of the simulation, there might encounter PBF causing some nodes problem, but with the distributed ledger technology, the non-fault nodes can reach consensus to make the transaction succeed and correct.
One example of BFT in use is bitcoin, a peer-to-peer digital currency system. The bitcoin network works in parallel to generate a chain of Hashcash style proof-of-work. The proof-of-work chain is the key to overcome Byzantine failures and to reach a coherent global view of the system state.

In our system, the application basically simulates the account transactions (deposit, withdraw, move, etc) of the bank system, which is distributed with data replicated. To simulate the Byzantine fault during the process, some fundamental standups below are giving us a

a. Any node can crash and recover at any time.
b. Use UDP to communicate between replicas, so the messages sent to each node might be lost, duplicated or disordered;
c. Client send request to replica to deposit and retrieve money, and double check the consistency between replicas.
d. Anytime with the 3f + 1 nodes, the system is able to survive f fault nodes.

2. Background

Figure 1 shows a normal case operation described in the paper. With four replicas (one primary) the system is able to tolerate one faulty node at a time.

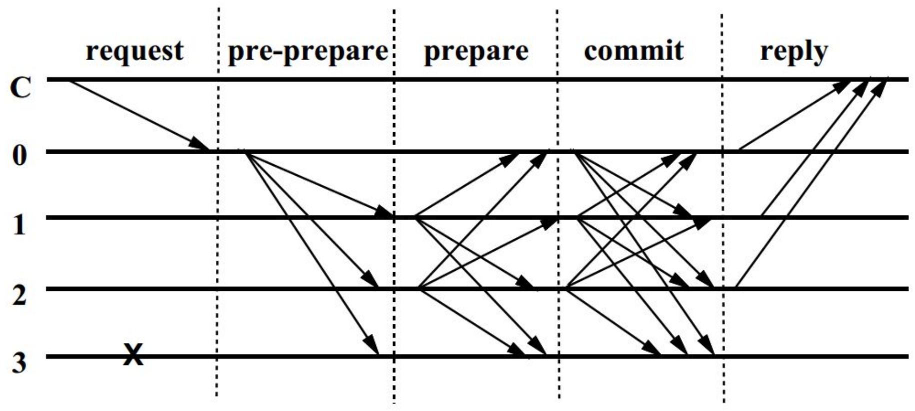


Figure 1.

Another important protocol is checkpoint. we will describe more detail of checkpoint endpoints in Section 3, here we only pinpoint that the checkpoint and digest are important to maintain data consistency in database.

3. Distributed Ledger

Basic: Build account database (including account information, balance, etc.) and replicated it into multiple nodes. Launch replica process in each replica node and each Process or some Processes share one database;
Distributed: a distributed ledger is a peer-to-peer system, each node can do transaction (communicate with other node) asynchronously;

1.1) support command line input to start the transaction in the client, eg:
get current balance for A
deposit $100 to A
move $100 from B to A
withdraw $200 from B

1.2) Information updated automatically among different nodes. The consensus among the working nodes is supported by PBFT, and we also rely on database's log system to commit, redo and undo. After the consensus and commit, the information should be updated into each replica;

1.3) Simulate PBFT to cause some nodes failed during the transaction. Since the messages are transferred with UDP, which is not reliable, the system can detect and process UDP related issues to keep accordance. We also manually shut down replica to simulate fault process.

4. Implementation

4.1 **PBFT Service**

We reuse MIT BFT open source library [2], and sfslite, a cryptography software tool [3] to help design our PBFT service.
The *libbyz* library implement the PBFT algorithm described in the paper. It provides one client interface *invoke*, which sends the request operation to replicas, and one main server side interface *execute*, to receive and execute the requested operations.
The *mysql* library provides the endpoints connected to Mysql database, it has two interface for both single-thread and multi-thread execution.
The *PBFTservice* library provide the endpoint to connect between PBFT distributed system and databases. And it simulated some simple transaction samples.
The service system is shown in Figure 2.

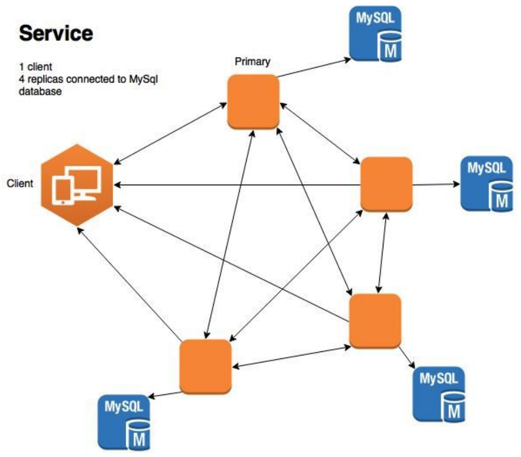


Figure 2.

For each replica:

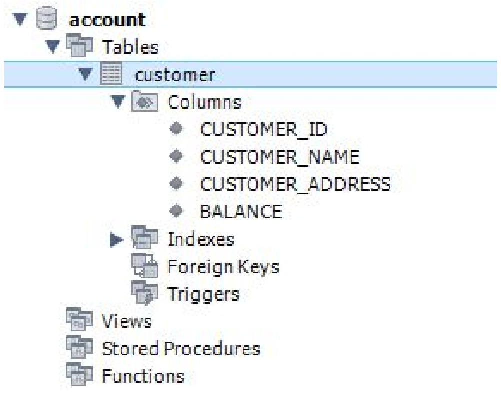
- wait infinitely for new transaction log.
- For the primary node, receive the input transaction from client and multicast to other replicas.
- Each replica will communicate with DB to execute and commit with log read and write one they receive the request.
- Communicate with other nodes with log read and write.

4.2) **AWS environment setup**

We initiated five AWS instances for simulating the distributed system. We will not give too much detail about the environment. But we are using network packet IO data to evaluate the throughput of the system. This can be optimized to use other AWS services to have more accurate evaluation.

4.3) **Database**

Install MySql Workbench to create bank account database, the table structure is like:



```
▼ account
  ▼ Tables
    ▼ customer
      ▼ Columns
          CUSTOMER_ID
          CUSTOMER_NAME
          CUSTOMER_ADDRESS
          BALANCE
      ▶ Indexes
        Foreign Keys
        Triggers
  Views
  Stored Procedures
  Functions
```

We implement connection pool in the replica to communicate between each replica and database, so the transaction is committed within the connection pool managed by each replica. Also MySql provide interfaces to maintain and manage the log and data and called by the replicas and clients.

5. Simulation

The main procedure involves three steps:

1) The client main procedure start transaction;
2) The replica main procedures start the pbft phases;
3) The replica executes the request and persists result into MySQL db in the commit phase (after committed-local is true).

We will present more specific details in the Appendix Cases. You can have a better understanding of how we simulate the protocols.

6. Discussion

correctness

1. The system can run successfully with at most 1 fault node, the remaining replicas keep consistent.
2. The combination of *view_change* and *check_point* enable the replicas to have consistency data after a node recover from the network partition (but it cannot recover from crash, because we don't persist logs into disk, while we do persist current state into db). Basically the returned replica can obtain missing messages from other replicas.

performance

1. We run simulation in both read-only mode and read-write mode. In the read-write mode, there are 50% read operations and 50% write executed in random sequence. The read-only mode is about 1.7 times faster than the read-write mode, which is as expected

because of the read-only optimization in PBFT algorithms.

Table 1 Simulation result. No.iterations: the number of iteration, read: the number of read operation, write: the number of write operation per simulation. time: the avg response time of a request. view_change: how many view_change happened in the simulation (totally). network partition times: manually turn down the aws network and then turn it on.

No. iterations	read	write	time(ms)/request	view_change	network partition times
1000	1000	0	1.34	0	0
1000	500	500	2.31	3	0
5000	2500	2500	2.56	5	1
10000	5000	5000	2.35	4	2

Table 1.

2. While restart the fault server the operation slow down dramatically. We assume it is because after the replica comes back to network, there are more communications between replicas and clients to resume lost messages, which will consume more times.

7. Improvement

An interesting implementation of PBFT is the peer-to-peer transaction system. For instance, some of the blockchain techniques are using the *Proof-of-work* based on the PBFT algorithm, which would be an future development of our system.

8. Conclusion and Acknowledgement

The main goal of the project is to get all of us more familiar with the PBFT protocols. Even though the algorithm is published about 20 years ago, we can still find its significant influence over the technology world. We started from implementing the algorithm, integrating open source tools, and then proceeded to simulating the transaction and distributing it to databases. Finally now we have better understanding of the PBFT not only its protocol, but also its implement. Even the simulation is simple and may contain flaws while handling complicated cases, but it is enough to maintain as a study case, which can be scale up to larger systems, and can be further designed to peer-to-peer transaction system.

9. Reference

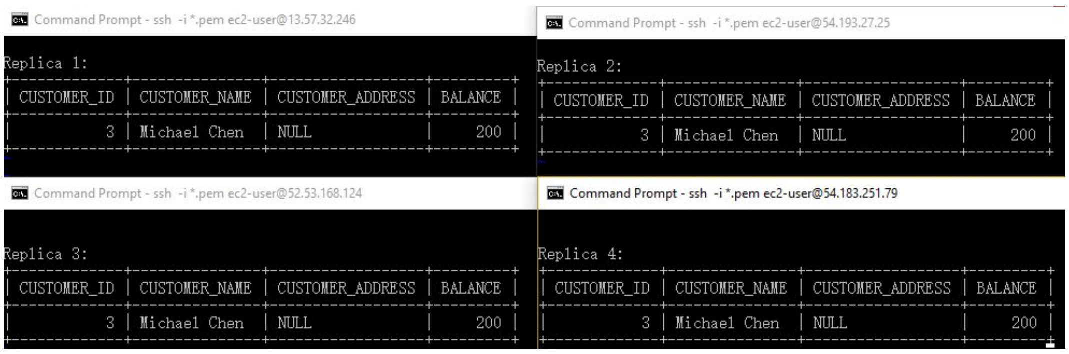
[1] Castro, Miguel, and Barbara Liskov. "Practical Byzantine fault tolerance." OSDI. Vol. 99. 1999.
[2] Programming Methodology Group, MIT, http://www.pmg.csail.mit.edu/bft/
[3] Sfslite, https://github.com/OkCupid/sfslite/wiki
[4] Source code: https://github.com/cmuhao/CS244b_final_project

Appendix

1) Experiment 1: write one and read, which means replicas show the specified one customer's balance related information after it wirted.

   Request from client: **deposit A 100, get A**

   Result from replicas:



```
Command Prompt - ssh -i *.pem ec2-user@13.57.32.246

Replica 1:
+-------------+---------------+------------------+---------+
| CUSTOMER_ID | CUSTOMER_NAME | CUSTOMER_ADDRESS | BALANCE |
+-------------+---------------+------------------+---------+
|           3 | Michael Chen  | NULL             |     200 |
+-------------+---------------+------------------+---------+
```

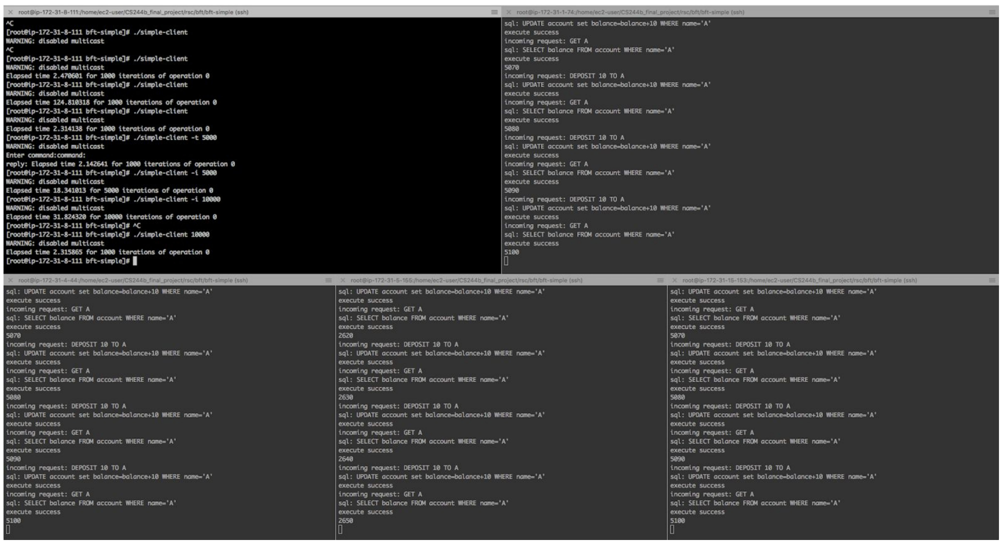
```
Command Prompt - ssh -i *.pem ec2-user@54.193.27.25

Replica 2:
+-------------+---------------+------------------+---------+
| CUSTOMER_ID | CUSTOMER_NAME | CUSTOMER_ADDRESS | BALANCE |
+-------------+---------------+------------------+---------+
|           3 | Michael Chen  | NULL             |     200 |
+-------------+---------------+------------------+---------+
```

```
Command Prompt - ssh -i *.pem ec2-user@52.53.168.124

Replica 3:
+-------------+---------------+------------------+---------+
| CUSTOMER_ID | CUSTOMER_NAME | CUSTOMER_ADDRESS | BALANCE |
+-------------+---------------+------------------+---------+
|           3 | Michael Chen  | NULL             |     200 |
+-------------+---------------+------------------+---------+
```

```
Command Prompt - ssh -i *.pem ec2-user@54.183.251.79

Replica 4:
+-------------+---------------+------------------+---------+
| CUSTOMER_ID | CUSTOMER_NAME | CUSTOMER_ADDRESS | BALANCE |
+-------------+---------------+------------------+---------+
|           3 | Michael Chen  | NULL             |     200 |
+-------------+---------------+------------------+---------+
```

2) Experiment 2: 1000, 5000, and 10000 iterations, random deposit and withdrawal.

   Result from replicas:



```
root@ip-172-31-8-111:/home/ec2-user/CS244b_final_project/rsc/bft/bft-simple (ssh)
^C
[root@ip-172-31-8-111 bft-simple]# ./simple-client
WARNING: disabled multicast
^C
[root@ip-172-31-8-111 bft-simple]# ./simple-client
WARNING: disabled multicast
Elapsed time 2.470601 for 1000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# ./simple-client
WARNING: disabled multicast
Elapsed time 124.810318 for 1000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# ./simple-client
WARNING: disabled multicast
Elapsed time 2.314138 for 1000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# ./simple-client -t 5000
WARNING: disabled multicast
Enter command:command:
reply: Elapsed time 2.142641 for 1000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# ./simple-client -i 5000
WARNING: disabled multicast
Elapsed time 18.341013 for 5000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# ./simple-client -i 10000
WARNING: disabled multicast
Elapsed time 31.824320 for 10000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# ^C
[root@ip-172-31-8-111 bft-simple]# ./simple-client 10000
WARNING: disabled multicast
Elapsed time 2.315865 for 1000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# █
```

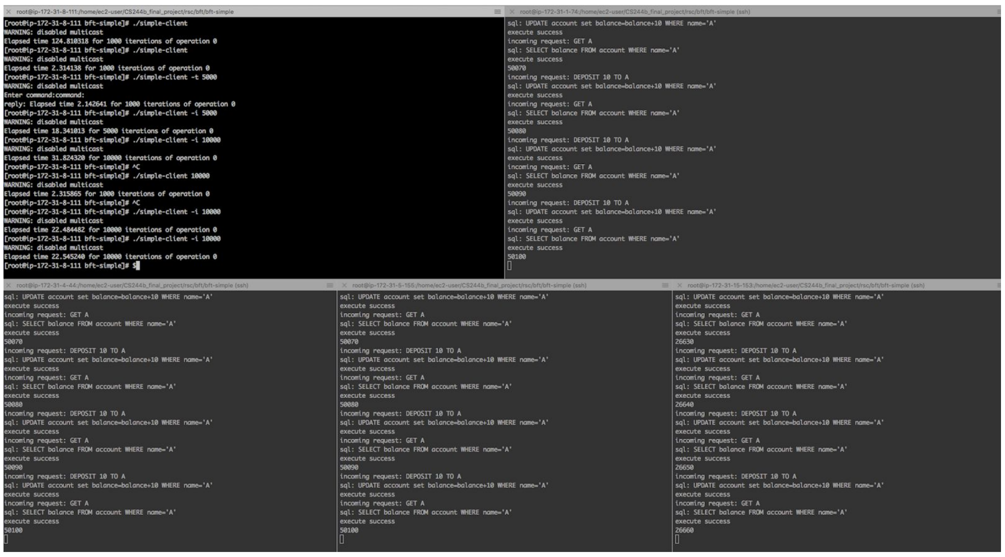
```
root@ip-172-31-1-74:/home/ec2-user/CS244b_final_project/rsc/bft/bft-simple (ssh)
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
5070
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
5080
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
5090
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
5100
▯
```

```
root@ip-172-31-4-44:/home/ec2-user/CS244b_final_project/rsc/bft/bft-simple (ssh)
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
5070
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
5080
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
5090
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
5100
▯
```

```
root@ip-172-31-5-155:/home/ec2-user/CS244b_final_project/rsc/bft/bft-simple (ssh)
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
2620
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
2630
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
2640
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
2650
▯
```

```
root@ip-172-31-15-153:/home/ec2-user/CS244b_final_project/rsc/bft/bft-simple (ssh)
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
5070
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
5080
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
5090
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
5100
▯
```

(1000 iterations)



```
root@ip-172-31-8-111:/home/ec2-user/CS244b_final_project/rsc/bft/bft-simple
[root@ip-172-31-8-111 bft-simple]# ./simple-client
WARNING: disabled multicast
Elapsed time 124.810318 for 1000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# ./simple-client
WARNING: disabled multicast
Elapsed time 2.314138 for 1000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# ./simple-client -t 5000
WARNING: disabled multicast
Enter command:command:
reply: Elapsed time 2.142641 for 1000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# ./simple-client -i 5000
WARNING: disabled multicast
Elapsed time 18.341013 for 5000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# ./simple-client -i 10000
WARNING: disabled multicast
Elapsed time 31.824320 for 10000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# ^C
[root@ip-172-31-8-111 bft-simple]# ./simple-client 10000
WARNING: disabled multicast
Elapsed time 2.315865 for 1000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# ^C
[root@ip-172-31-8-111 bft-simple]# ./simple-client -i 10000
WARNING: disabled multicast
Elapsed time 22.484482 for 10000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# ./simple-client -i 10000
WARNING: disabled multicast
Elapsed time 22.545240 for 10000 iterations of operation 0
[root@ip-172-31-8-111 bft-simple]# $
```

```
root@ip-172-31-1-74:/home/ec2-user/CS244b_final_project/rsc/bft/bft-simple (ssh)
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
50070
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
50080
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
50090
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
50100
```

```
root@ip-172-31-4-44:/home/ec2-user/CS244b_final_project/rsc/bft/bft-simple (ssh)
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
50070
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
50080
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
50090
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
50100
```

```
root@ip-172-31-5-155:/home/ec2-user/CS244b_final_project/rsc/bft/bft-simple (ssh)
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
50070
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
50080
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
50090
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
50100
```

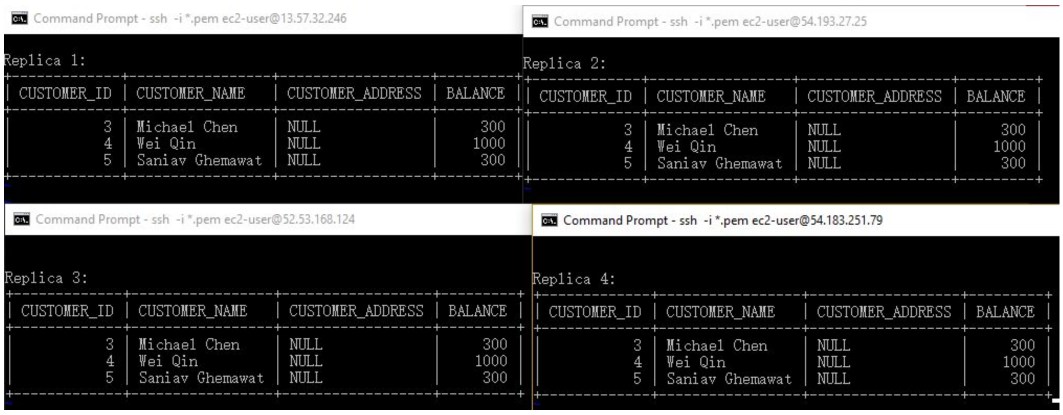
```
root@ip-172-31-15-153:/home/ec2-user/CS244b_final_project/rsc/bft/bft-simple (ssh)
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
26630
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
26640
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
26650
incoming request: DEPOSIT 10 TO A
sql: UPDATE account set balance=balance+10 WHERE name='A'
execute success
incoming request: GET A
sql: SELECT balance FROM account WHERE name='A'
execute success
26660
```

(10000 iterations)

3) Experiment 3: write some and read, which means replicas show the specified customers' balance related information after they writed.

Request from client: **deposit A 100, get A, deposit B 200, get B, withdraw C 100, get C**

Result from replicas:



```
Command Prompt - ssh -i *.pem ec2-user@13.57.32.246

Replica 1:
+-------------+----------------+------------------+---------+
| CUSTOMER_ID | CUSTOMER_NAME  | CUSTOMER_ADDRESS | BALANCE |
+-------------+----------------+------------------+---------+
|           3 | Michael Chen   | NULL             |     300 |
|           4 | Wei Qin        | NULL             |    1000 |
|           5 | Saniav Ghemawat| NULL             |     300 |
+-------------+----------------+------------------+---------+
```

```
Command Prompt - ssh -i *.pem ec2-user@54.193.27.25

Replica 2:
+-------------+----------------+------------------+---------+
| CUSTOMER_ID | CUSTOMER_NAME  | CUSTOMER_ADDRESS | BALANCE |
+-------------+----------------+------------------+---------+
|           3 | Michael Chen   | NULL             |     300 |
|           4 | Wei Qin        | NULL             |    1000 |
|           5 | Saniav Ghemawat| NULL             |     300 |
+-------------+----------------+------------------+---------+
```

```
Command Prompt - ssh -i *.pem ec2-user@52.53.168.124

Replica 3:
+-------------+----------------+------------------+---------+
| CUSTOMER_ID | CUSTOMER_NAME  | CUSTOMER_ADDRESS | BALANCE |
+-------------+----------------+------------------+---------+
|           3 | Michael Chen   | NULL             |     300 |
|           4 | Wei Qin        | NULL             |    1000 |
|           5 | Saniav Ghemawat| NULL             |     300 |
+-------------+----------------+------------------+---------+
```

```
Command Prompt - ssh -i *.pem ec2-user@54.183.251.79

Replica 4:
+-------------+----------------+------------------+---------+
| CUSTOMER_ID | CUSTOMER_NAME  | CUSTOMER_ADDRESS | BALANCE |
+-------------+----------------+------------------+---------+
|           3 | Michael Chen   | NULL             |     300 |
|           4 | Wei Qin        | NULL             |    1000 |
|           5 | Saniav Ghemawat| NULL             |     300 |
+-------------+----------------+------------------+---------+
```