University of St Andrews

Distributed Systems

CS4103

Ring-Based Distributed System

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April 25, 2019

Goal

To demonstrate an understanding of leader election and mutual exclusion in distributed systems by developing a ring-based distributed social media application.

Contents

1 Initial Set-up **1**

2 Ring Formation **1**
2.1 Messages 1
2.2 Transport Protocol 2
2.3 Initialization and Joining 3
2.4 Topology Recovery and Maintenance 5
2.5 Topology Persistence 7

3 Leader/Coordinator Election **9**
3.1 Election API 9
3.2 Triggering Elections 11
3.3 Ring-Based 11
3.4 Chang Roberts 12
3.5 Bully 12

4 Receive/Send Posts **14**
4.1 Mutual Exclusion 14
4.2 Server 15
4.3 Client (RingChat) 17

5 Testing **17**

6 Potential Issues **19**

7 Summary **19**

8 How to Run **20**

1 Initial Set-up

Java 8 was chosen for this project due to it's friendly socket API, and Maven [1] was used as the build tool.

Since each node would be running on an isolated machine, the planned testing environment would involve using *ssh* to start the nodes remotely. Providing the configuration as command line arguments was considered simpler than other methods, and was implemented using the Apache Commons CLI library [2]. In order to run the program, the arguments shown in table 1 need to be supplied. The purpose of each argument is explained later.

usage: java -jar ⟨program⟩-with-dependencies.jar

-d,–drop	Include if this node should trigger a database refresh.
-e,–election ⟨arg⟩	Election method to use.
-f,–list ⟨arg⟩	Path to file containing list of nodes (resource P).
-i,–id ⟨arg⟩	ID of this node.

Table 1: Arguments for running application.

2 Ring Formation

2.1 Messages

In order for nodes to understand and parse the messages that were sent between them, a message protocol was designed. Figure 1 shows the header that would be part of every message sent. The possible types of messages are summarised in table 2.

The messages are sent as serialized Java objects, which requires that all message classes implement the *Serializable* interface. A more platform independent format such as JSON would be preferred, but since all nodes would be running the same ring client this method of serializing messages was kept. Figure 2 shows the header for an election message. Election messages are sent in the payload of main messages.

Message Type	Usage	Payload
JOIN	Sent by new node to coordinator when wanting to join ring.	None
SUCCESSOR	Sent by coordinator to inform a node to connect to a new successor.	New Successor ID
SUCCESSOR_REQUEST	Sent by a node to the coordinator after its successor has failed in order to be reassigned a successor.	None
TOKEN	Sent by a node to its successor.	None
TOKEN_ACK	Sent by a node to its predecessor after receiving the token to confirm its reception.	None
COORDINATOR_ELECTION	Message payload contains an election message.	Election Message

Table 2: Possible values for the type field in the message header, with their usage and payload.

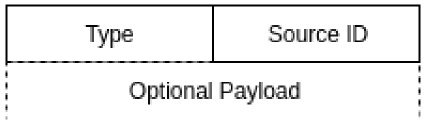


Figure 1: Main message header.

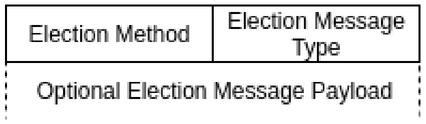


Figure 2: Election message header.

2.2 Transport Protocol

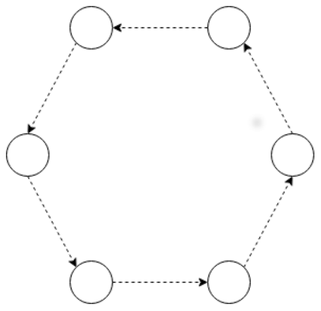
Due to different patterns of communication being required for token passing and coordination, both TCP and UDP were used for this project, as shown in Figure 3.

TCP was used for communication **around** the ring:

1. Reliable communication avoids token being lost.
2. Connection is reused frequently between predecessors and successors, justifying handshake overhead.
3. Failure can be detected immediately when trying to read or write to a TCP socket.

UDP was used for communication **across** the ring:

1. Low communication overhead allows for messagees to be sent to multiple nodes quickly, improving recovery time from node failure.
2. No session maintenance allows coordinator to handle more members in the ring.
3. Multicast communication possible which would greatly simplify broadcasting.


(a) TCP Around Ring

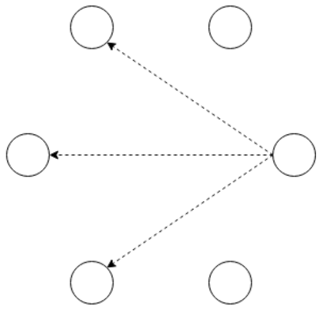

(b) UDP Across Ring

Figure 3: The different types of communication used

2.3 Initialization and Joining

On initialization, each node sends out join messagees to the coordinator. The joining protocol is based on [3], and is shown in Figure 4. Figure 5 shows how the state of each connection changes over the course of the joining procedure.

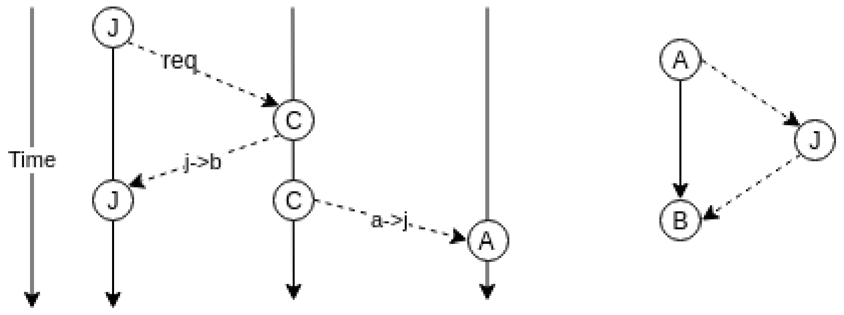


Figure 4: Joining protocol over time, with topology shown on right.

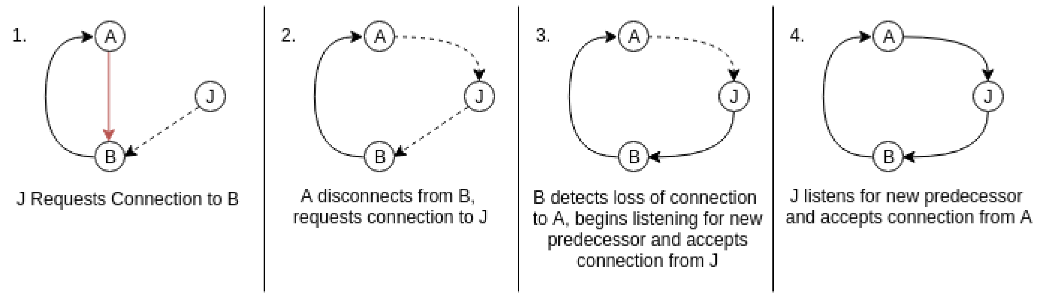

1.
A
J
B
J Requests Connection to B
2.
A
J
B
A disconnects from B, requests connection to J
3.
A
J
B
B detects loss of connection to A, begins listening for new predecessor and accepts connection from J
4.
A
J
B
J listens for new predecessor and accepts connection from A

Figure 5: State of each connection as a new node joins the ring. The red arrow shows the edge that is replaced with the new node, and solid and dashed arrows represent ongoing and pending connections respectively. Either A or B can be the coordinator in this scenario.

When node J wants to join the ring:

1. J sends join request to coordinator C.
2. C sends successor to J, telling it to connect to B.
3. C sends successor to A, telling it to connect to J.
4. A disconnects from B, B begins listening for new predecessor.
5. J connects to B, A connects to J.

In order for this process to work for a ring network with a single node, it required another thread to wait on the incoming connection, and the main thread would then request the connection to itself.

Figure 6 shows the logs from node 2 as it joins the ring, and figure 7 shows the logs from the coordinator as it handles the request. Figure 8 shows the logs from node 6 when it initializes the ring network by connecting to itself.

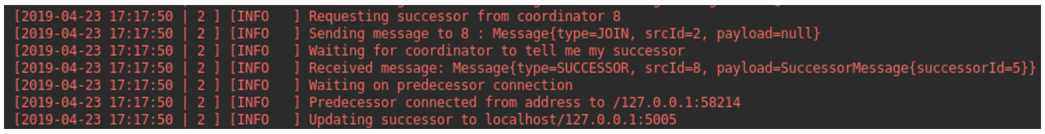
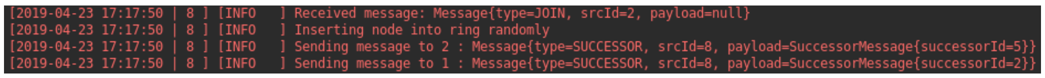
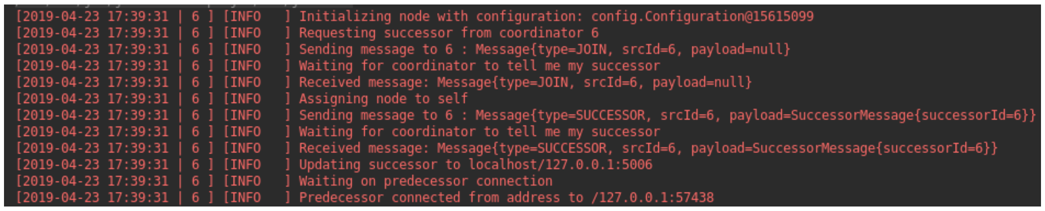

```
[2019-04-23 17:17:50 | 2 ] [INFO   ] Requesting successor from coordinator 8
[2019-04-23 17:17:50 | 2 ] [INFO   ] Sending message to 8 : Message{type=JOIN, srcId=2, payload=null}
[2019-04-23 17:17:50 | 2 ] [INFO   ] Waiting for coordinator to tell me my successor
[2019-04-23 17:17:50 | 2 ] [INFO   ] Received message: Message{type=SUCCESSOR, srcId=8, payload=SuccessorMessage{successorId=5}}
[2019-04-23 17:17:50 | 2 ] [INFO   ] Waiting on predecessor connection
[2019-04-23 17:17:50 | 2 ] [INFO   ] Predecessor connected from address to /127.0.0.1:58214
[2019-04-23 17:17:50 | 2 ] [INFO   ] Updating successor to localhost/127.0.0.1:5005
```

Figure 6: Logs from node 2 when joining the ring with coordinator ID 8.



```
[2019-04-23 17:17:50 | 8 ] [INFO   ] Received message: Message{type=JOIN, srcId=2, payload=null}
[2019-04-23 17:17:50 | 8 ] [INFO   ] Inserting node into ring randomly
[2019-04-23 17:17:50 | 8 ] [INFO   ] Sending message to 2 : Message{type=SUCCESSOR, srcId=8, payload=SuccessorMessage{successorId=5}}
[2019-04-23 17:17:50 | 8 ] [INFO   ] Sending message to 1 : Message{type=SUCCESSOR, srcId=8, payload=SuccessorMessage{successorId=2}}
```

Figure 7: Logs from coordinator node 8 when node 2 wishes to join.



```
[2019-04-23 17:39:31 | 6 ] [INFO   ] Initializing node with configuration: config.Configuration@15615099
[2019-04-23 17:39:31 | 6 ] [INFO   ] Requesting successor from coordinator 6
[2019-04-23 17:39:31 | 6 ] [INFO   ] Sending message to 6 : Message{type=JOIN, srcId=6, payload=null}
[2019-04-23 17:39:31 | 6 ] [INFO   ] Waiting for coordinator to tell me my successor
[2019-04-23 17:39:31 | 6 ] [INFO   ] Received message: Message{type=JOIN, srcId=6, payload=null}
[2019-04-23 17:39:31 | 6 ] [INFO   ] Assigning node to self
[2019-04-23 17:39:31 | 6 ] [INFO   ] Sending message to 6 : Message{type=SUCCESSOR, srcId=6, payload=SuccessorMessage{successorId=6}}
[2019-04-23 17:39:31 | 6 ] [INFO   ] Waiting for coordinator to tell me my successor
[2019-04-23 17:39:31 | 6 ] [INFO   ] Received message: Message{type=SUCCESSOR, srcId=6, payload=SuccessorMessage{successorId=6}}
[2019-04-23 17:39:31 | 6 ] [INFO   ] Updating successor to localhost/127.0.0.1:5006
[2019-04-23 17:39:31 | 6 ] [INFO   ] Waiting on predecessor connection
[2019-04-23 17:39:31 | 6 ] [INFO   ] Predecessor connected from address to /127.0.0.1:57438
```

Figure 8: Logs from node 6 when it initializes the ring network and connects to itself.

2.4 Topology Recovery and Maintenance

When designing a distributed system, it should be assumed that failure will occur, and so as an extension this implementation included a mechanism for recovering from node failure. Node failure is detected by either:

1. A node attempting to read the socket connected to its predecessor.
2. A node forwarding the token to its successor and not receiving an acknowledgement within a given timeframe.

When a failure is detected by the successor of a failing node, it will simply begin listening for a new predecessor. Once the predecessor of the failing node detects the loss of connection, it will request a new successor from the coordinator node. The coordinator will then reply with the ID of the node after the failed node for the original predeccessor to connect to, at which point normal network behaviour can resume. Figure 9 shows the topology change when a node fails. Since the failure is detected by the ring handling thread, and the new successor message arrives on the UDPSocket handling thread, the ring handling thread simply blocks until notified by the UDPSocket thread that a new successor has now been connected to.

The token acknowledgement message is the only occurence of communication in the reverse direction of the ring topology. The predecessor of the failing node will hold onto the token until it is assigned a new successor, and will only release the token once it has received an acknowledgement from its successor. THis ensures that the token will not be lost in transport.

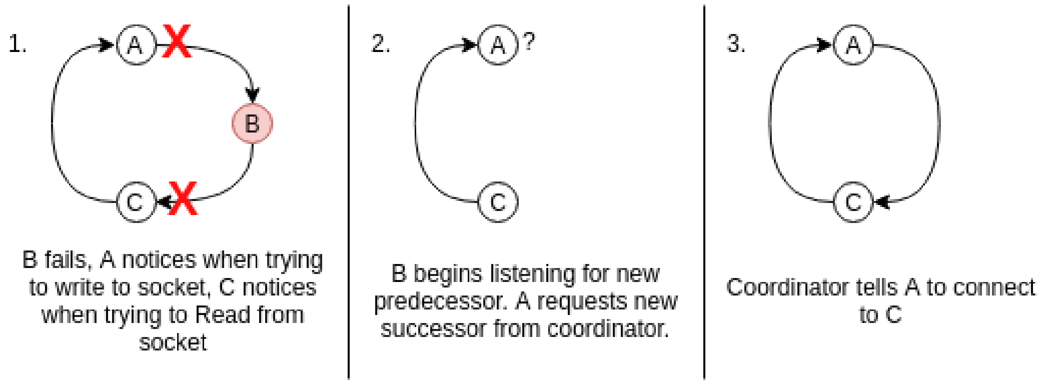
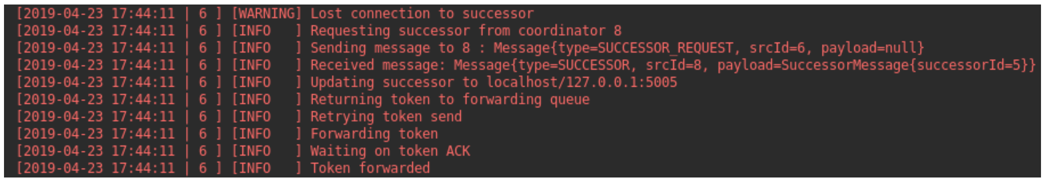

1.
A
B
C
B fails, A notices when trying to write to socket, C notices when trying to Read from socket
2.
A
?
C
B begins listening for new predecessor. A requests new successor from coordinator.
3.
A
C
Coordinator tells A to connect to C

Figure 9: Network topology during the recovery from node B failing. Either A or C are the coordinator in this scenario.

However, if somehow the token is acknowledged but the acknowledgement message does not reach the predecessor in time, it could be possible for two tokens to then be in circulation. Figure 10 shows logs from a node that has experienced successor failure.



```
[2019-04-23 17:44:11 | 6 ] [WARNING] Lost connection to successor
[2019-04-23 17:44:11 | 6 ] [INFO   ] Requesting successor from coordinator 8
[2019-04-23 17:44:11 | 6 ] [INFO   ] Sending message to 8 : Message{type=SUCCESSOR_REQUEST, srcId=6, payload=null}
[2019-04-23 17:44:11 | 6 ] [INFO   ] Received message: Message{type=SUCCESSOR, srcId=8, payload=SuccessorMessage{successorId=5}}
[2019-04-23 17:44:11 | 6 ] [INFO   ] Updating successor to localhost/127.0.0.1:5005
[2019-04-23 17:44:11 | 6 ] [INFO   ] Returning token to forwarding queue
[2019-04-23 17:44:11 | 6 ] [INFO   ] Retrying token send
[2019-04-23 17:44:11 | 6 ] [INFO   ] Forwarding token
[2019-04-23 17:44:11 | 6 ] [INFO   ] Waiting on token ACK
[2019-04-23 17:44:11 | 6 ] [INFO   ] Token forwarded
```

Figure 10: Logs from node 6 when it's successor fails to acknowledge it's sent token.

During testing, an edge case was realised with this recovery mechanism. If the disconnect is discovered when reading from the predecessor socket, there is a case where just waiting for a new predecessor does not work. Figure 11 shows two scenarios where the disconnect is realised while reading from the predecessor socket.

The scenario on the left would require A to first designate itself as its new successor before performing the self connection procedure described in the initialization protocol. This would only be necessary if the network consisted of two nodes, otherwise another node would eventually connect to A. The scenario on the right however is not one where an actual failure has occurred, and instead A is just changing its predecessor from itself to B. In order to check that the disconnect had occurred not because of failure, the token ring socket class (*RingCommunicationHandler*) provided a boolean flag that would be true if the most recent disconnect had occurred while connected to itself.

Knowing this meant that it could be assumed if there were only two nodes in the network that the other node has failed, and so a self connection would have to be performed as described in the previous section.

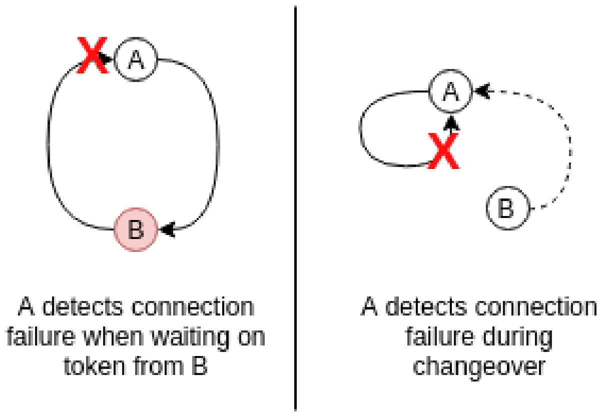

A
B
A detects connection failure when waiting on token from B
A
B
A detects connection failure during changeover

Figure 11: Two predecessor disconnect scenarios that are identical to the thread polling the predecessor socket.

2.5 Topology Persistence

Initially, the coordinator node was always the node with the ID 6. This node would maintain an in-memory virtual representation of the network topology using a cyclic linked list of node IDs. This obviously would be useless if the coordinator was to change, and so it was necessary to persist the network topology somehow.

This was achieved by adding a database which would behave like resource P in the practical specification (the list of nodes). Only the coordinator would be able to write and update the database, and all other nodes could only read from it. The database allowed operations to be carried out as transactions, meaning that node failure during an update could be rolled back. The database is initialized using a csv file containing the ID, address, and port of each node that *may* join the network at some point. Figure 12 shows an ER diagram of the database schema for persisting nodes. The successorId is nullable and refers to another row in the node table. If a value is present in that column then the node ID on that row would be assumed to be part of the ring.

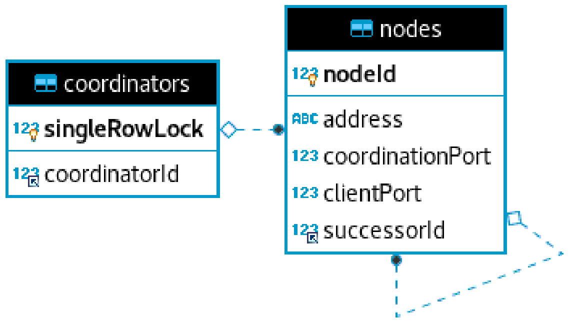


Figure 12: ER diagram of the database schema for persisting the network topology.

When a new node wants to join the network, it first queries the database to learn who the current coordinator is. If no coordinator exists and no nodes have successors set, then this node will assume coordinator status. A limitation of this functionality is that if another node (B) queries for the current coordinator before the first node (A) has had the chance to update the database, then B could potentially also designate itself as coordinator. Since B would overwrite A as coordinator, later joining nodes would always make requests to B, and A would remain connected to itself, each 'ring' with its own token (the split brain problem).

The database was essential for recovering the network topology quickly when a coordinator failed. If a node detected the failure of its successor and knew that its successor was currently the coordinator, it would temporarily act as a coordinator until a new one was elected. This would allow it to update the database and recover the ring topology by connecting to the successor of the failed coordinator. Immediately after recovering this connection, an election would be triggered by the acting coordinator in order to designate a permanent coordinator.

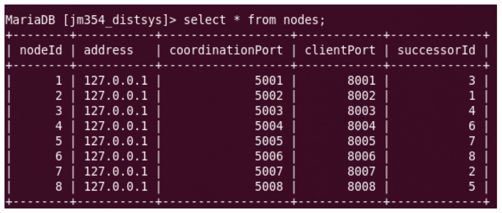
In order to ensure that only one coordinator existed at any time, the coordinators table included a boolean column *singleRowLock* that would always be true. By setting this boolean column as the primary key, insert statements could then be constructed to either

1. Insert a new row if no coordinator exists with the value TRUE for *singleRowLock*.

2. Change the value of the coordinator ID if a row already exists by using the 'ON DUPLICATE KEY UPDATE' statement in the INSERT statement.

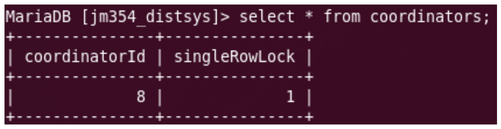
Whilst another row could be added with the value FALSE for *singleRowLock*, permissions would be configured such that only the hosts and a system administrator would be able to perform updates so it could be assumed that as long as the application code always used TRUE for inserts, only one row would ever exist.

Figure 13 shows the state of the database after 8 nodes join in a random order. Figure 14 shows the state of the database after node 8 fails and a new coordinator is elected.



```
MariaDB [jm354_distsys]> select * from nodes;
+--------+-----------+------------------+------------+-------------+
| nodeId | address   | coordinationPort | clientPort | successorId |
+--------+-----------+------------------+------------+-------------+
|      1 | 127.0.0.1 |             5001 |       8001 |           3 |
|      2 | 127.0.0.1 |             5002 |       8002 |           1 |
|      3 | 127.0.0.1 |             5003 |       8003 |           4 |
|      4 | 127.0.0.1 |             5004 |       8004 |           6 |
|      5 | 127.0.0.1 |             5005 |       8005 |           7 |
|      6 | 127.0.0.1 |             5006 |       8006 |           8 |
|      7 | 127.0.0.1 |             5007 |       8007 |           2 |
|      8 | 127.0.0.1 |             5008 |       8008 |           5 |
+--------+-----------+------------------+------------+-------------+
```

(a) Node database table.



```
MariaDB [jm354_distsys]> select * from coordinators;
+---------------+---------------+
| coordinatorId | singleRowLock |
+---------------+---------------+
|             8 |             1 |
+---------------+---------------+
```

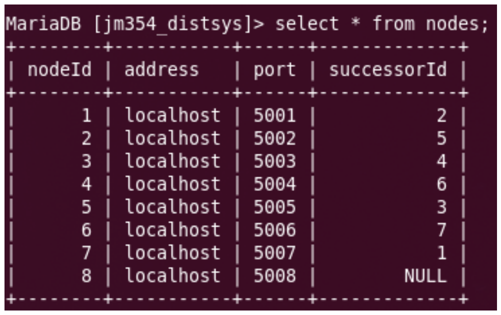
(b) Coordinator database table.

Figure 13: The state of the database after nodes join in the order 6, 5, 8, 3, 4, 7, 1, 2.

3 Leader/Coordinator Election

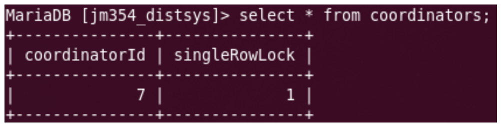
3.1 Election API

An interface was used for providing a generic 'election algorithm' API, allowing different algorithms to be switched out easily. Any messagees that arrived from either the UDP socket or the ring sockets that had the COORDINATOR_ELECTION type would be routed to the handler for the election



```
MariaDB [jm354_distsys]> select * from nodes;
+--------+-----------+------+-------------+
| nodeId | address   | port | successorId |
+--------+-----------+------+-------------+
|      1 | localhost | 5001 |           2 |
|      2 | localhost | 5002 |           5 |
|      3 | localhost | 5003 |           4 |
|      4 | localhost | 5004 |           6 |
|      5 | localhost | 5005 |           3 |
|      6 | localhost | 5006 |           7 |
|      7 | localhost | 5007 |           1 |
|      8 | localhost | 5008 |        NULL |
+--------+-----------+------+-------------+
```

(a) Node database table.



```
MariaDB [jm354_distsys]> select * from coordinators;
+---------------+---------------+
| coordinatorId | singleRowLock |
+---------------+---------------+
|             7 |             1 |
+---------------+---------------+
```

(b) Coordinator database table.

Figure 14: The state of the database after recovering from node 8 failing.

algorithm specified in the election header. For example, an election message that required the bully algorithm would be routed to the bully election handler.

In the configuration for each node, a default election algorithm is specified. Therefore the type of election that would be started could vary depending on which node initiated it. If a node received an election message for a different algorithm to the one they are currently using, then they would replace their election handler with one that could process the arriving message.

The methods required by the election API are summarised in table 3. The constructors could vary since different resources may be necessary. For example, the ring-based and Chang Roberts algorithms both only require communication around the ring, whilst the Bully algorithm only requires communication across the ring.

Method	Usage
getMethodName	Returns the name of the underlying algorithm used by the implementation of this interface.
startElection	Starts an election.
handleMessage	Handles any election messagees.
getResult	Returns the result of the election (if concluded).
electionConcluded	Returns true if a result has been obtained.

Table 3: Methods of the election handler interface.

3.2 Triggering Elections

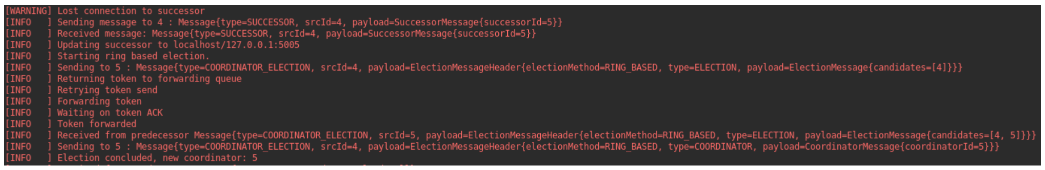
Initially, elections could only be triggered by the predecessor of a failed coordinator. This meant that if a new node joined with a higher ID, it would not be elected until the current coordinator failed. This was resolved by adding logic to the joining procedure that once part of the ring, the new node would trigger an election if it found that its ID was greater than the current coordinators.

This meant it would be possible for multiple elections to be ongoing simultaneously if many nodes joined the ring in quick succession with higher IDs than the current coordinator, or if coordinator failure occurred whilst a node with a higher ID joined the ring.

3.3 Ring-Based

The ring based algorithm was the simplest to implement and test. The node starting the election would initialise the ELECTION message with its own ID and forward this to its successor and set the *ongoing* flag to true. The message would be forwarded around the ring by each node after appending their ID to the list of candidates until it returned to the node that started the election.

This node then chose the new coordinator from the list of candidates based on which had the highest ID, and forwarded the result to its successors as a COORDINATOR message. The result would be forwarded by each node until it reached a node that was already aware of the new coordinator.



```
[WARNING] Lost connection to successor
[INFO   ] Sending message to 4 : Message{type=SUCCESSOR, srcId=4, payload=SuccessorMessage{successorId=5}}
[INFO   ] Received message: Message{type=SUCCESSOR, srcId=4, payload=SuccessorMessage{successorId=5}}
[INFO   ] Updating successor to localhost/127.0.0.1:5005
[INFO   ] Starting ring based election.
[INFO   ] Sending to 5 : Message{type=COORDINATOR_ELECTION, srcId=4, payload=ElectionMessageHeader{electionMethod=RING_BASED, type=ELECTION, payload=ElectionMessage{candidates=[4]}}}
[INFO   ] Returning token to forwarding queue
[INFO   ] Retrying token send
[INFO   ] Forwarding token
[INFO   ] Waiting on token ACK
[INFO   ] Token forwarded
[INFO   ] Received from predecessor Message{type=COORDINATOR_ELECTION, srcId=5, payload=ElectionMessageHeader{electionMethod=RING_BASED, type=ELECTION, payload=ElectionMessage{candidates=[4, 5]}}}
[INFO   ] Sending to 5 : Message{type=COORDINATOR_ELECTION, srcId=4, payload=ElectionMessageHeader{electionMethod=RING_BASED, type=COORDINATOR, payload=CoordinatorMessage{coordinatorId=5}}}
[INFO   ] Election concluded, new coordinator: 5
```

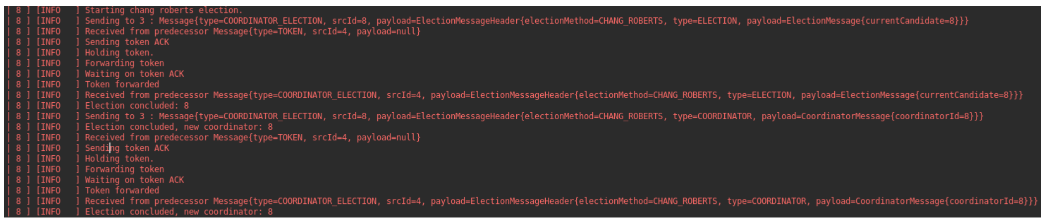
Figure 15: Logs from node 2 after detecting coordinator failure. Note how token passing resumes as soon as a new successor is found despite the loss of the coordinator in order to make node failure transparent.

3.4 Chang Roberts

The Chang Roberts algorithm reused most of the components from the ring-based algorithm, other than the forwarding logic for ELECTION messagees.

If the ELECTION message contained the receiving nodes ID, then it would conclude the election and forward the COORDINATOR message as in the ring-based algorithm. However, in order to avoid redundant forwarding of election messages if two or more elections are started at the same time, ELECTION messages would only be forwarded if the receiving node was a better candidate (i.e. had a greater ID), or if it had not already participated by forwarding a message previously.

Figure 16 shows logs from a new node that has joined the ring and triggered an election. Initially the election message is sent, and later it returns with the same ID and so node 8 elects itself. It then forwards the coordinator message until it arrives back to itself at which point it is dropped.



```
| 8 ] [INFO   ] Starting chang roberts election.
| 8 ] [INFO   ] Sending to 3 : Message{type=COORDINATOR_ELECTION, srcId=8, payload=ElectionMessageHeader{electionMethod=CHANG_ROBERTS, type=ELECTION, payload=ElectionMessage{currentCandidate=8}}}
| 8 ] [INFO   ] Received from predecessor Message{type=TOKEN, srcId=4, payload=null}
| 8 ] [INFO   ] Sending token ACK
| 8 ] [INFO   ] Holding token.
| 8 ] [INFO   ] Forwarding token
| 8 ] [INFO   ] Waiting on token ACK
| 8 ] [INFO   ] Token forwarded
| 8 ] [INFO   ] Received from predecessor Message{type=COORDINATOR_ELECTION, srcId=4, payload=ElectionMessageHeader{electionMethod=CHANG_ROBERTS, type=ELECTION, payload=ElectionMessage{currentCandidate=8}}}
| 8 ] [INFO   ] Election concluded: 8
| 8 ] [INFO   ] Sending to 3 : Message{type=COORDINATOR_ELECTION, srcId=8, payload=ElectionMessageHeader{electionMethod=CHANG_ROBERTS, type=COORDINATOR, payload=CoordinatorMessage{coordinatorId=8}}}
| 8 ] [INFO   ] Election concluded, new coordinator: 8
| 8 ] [INFO   ] Received from predecessor Message{type=TOKEN, srcId=4, payload=null}
| 8 ] [INFO   ] Sending token ACK
| 8 ] [INFO   ] Holding token.
| 8 ] [INFO   ] Forwarding token
| 8 ] [INFO   ] Waiting on token ACK
| 8 ] [INFO   ] Token forwarded
| 8 ] [INFO   ] Received from predecessor Message{type=COORDINATOR_ELECTION, srcId=4, payload=ElectionMessageHeader{electionMethod=CHANG_ROBERTS, type=COORDINATOR, payload=CoordinatorMessage{coordinatorId=8}}}
| 8 ] [INFO   ] Election concluded, new coordinator: 8
```

Figure 16: Logs from node 8 when it joins the ring and notices its ID is greater than the current coordinator.

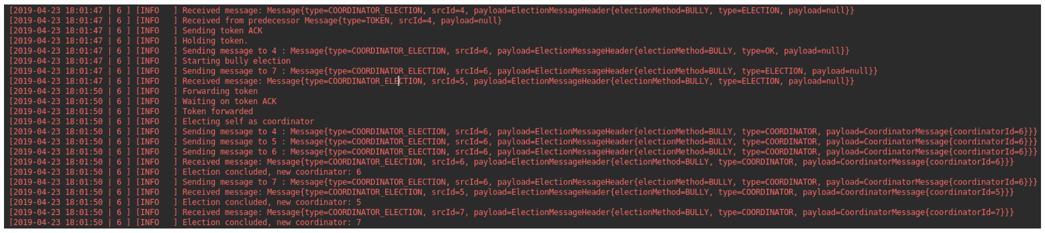
3.5 Bully

The bully algorithm was the most difficult to implement due to its dependence on timing. An election would be started by a node by sending an ELECTION message to all nodes with IDs greater than it's own. It would then create a thread which would sleep for a preset time before assuming it is to be the coordinator. If one of the other nodes that received the ELECTION message replied with an OK message, the sleeping thread would simply terminate after the preset time had expired. Another thread would be spawned to again sleep for a duration of time after receiving the OK message. If no coordinator message was received before this second duration elapsed, then the node would restart the election.

Each node that received an ELECTION message would reply with an OK message if it had not already started an election, and then carry out the same procedure as the first node had to trigger the election. Eventually the node with the highest ID would not have any other nodes to send ELECTION messagees to, and so it would consider itself the coordinator and inform all the other nodes in the ring using the COORDINATOR message.

Figure 17 shows how effective the bully algorithm is at dealing with failure and demonstrates a node being bullied into letting another node be coordinator. The order of events in the logs shown are:

1. Node 6 receives election message from node 4.
2. 6 replies with OK message, and begins its own election by sending an election message to node 7.
3. 6 also receives election message from node 5, but ignores it since it is already carrying out an election.
4. Timeout occurs without 7 sending OK message, 6 tries to elect self as coordinator and sends coordinator message to all other nodes.
5. Node 7 has in the meantime elected itself as coordinator, and 'bullies' node 6 into letting it be coordinator.



```
[2019-04-23 18:01:47 | 6 ] [INFO   ] Received message: Message{type=COORDINATOR_ELECTION, srcId=4, payload=ElectionMessageHeader{electionMethod=BULLY, type=ELECTION, payload=null}}
[2019-04-23 18:01:47 | 6 ] [INFO   ] Received from predecessor Message{type=TOKEN, srcId=4, payload=null}
[2019-04-23 18:01:47 | 6 ] [INFO   ] Sending token ACK
[2019-04-23 18:01:47 | 6 ] [INFO   ] Holding token.
[2019-04-23 18:01:47 | 6 ] [INFO   ] Sending message to 4 : Message{type=COORDINATOR_ELECTION, srcId=6, payload=ElectionMessageHeader{electionMethod=BULLY, type=OK, payload=null}}
[2019-04-23 18:01:47 | 6 ] [INFO   ] Starting bully election
[2019-04-23 18:01:47 | 6 ] [INFO   ] Sending message to 7 : Message{type=COORDINATOR_ELECTION, srcId=6, payload=ElectionMessageHeader{electionMethod=BULLY, type=ELECTION, payload=null}}
[2019-04-23 18:01:47 | 6 ] [INFO   ] Received message: Message{type=COORDINATOR_ELECTION, srcId=5, payload=ElectionMessageHeader{electionMethod=BULLY, type=ELECTION, payload=null}}
[2019-04-23 18:01:50 | 6 ] [INFO   ] Forwarding token
[2019-04-23 18:01:50 | 6 ] [INFO   ] Waiting on token ACK
[2019-04-23 18:01:50 | 6 ] [INFO   ] Token forwarded
[2019-04-23 18:01:50 | 6 ] [INFO   ] Electing self as coordinator
[2019-04-23 18:01:50 | 6 ] [INFO   ] Sending message to 4 : Message{type=COORDINATOR_ELECTION, srcId=6, payload=ElectionMessageHeader{electionMethod=BULLY, type=COORDINATOR, payload=CoordinatorMessage{coordinatorId=6}}}
[2019-04-23 18:01:50 | 6 ] [INFO   ] Sending message to 5 : Message{type=COORDINATOR_ELECTION, srcId=6, payload=ElectionMessageHeader{electionMethod=BULLY, type=COORDINATOR, payload=CoordinatorMessage{coordinatorId=6}}}
[2019-04-23 18:01:50 | 6 ] [INFO   ] Sending message to 6 : Message{type=COORDINATOR_ELECTION, srcId=6, payload=ElectionMessageHeader{electionMethod=BULLY, type=COORDINATOR, payload=CoordinatorMessage{coordinatorId=6}}}
[2019-04-23 18:01:50 | 6 ] [INFO   ] Received message: Message{type=COORDINATOR_ELECTION, srcId=6, payload=ElectionMessageHeader{electionMethod=BULLY, type=COORDINATOR, payload=CoordinatorMessage{coordinatorId=6}}}
[2019-04-23 18:01:50 | 6 ] [INFO   ] Election concluded, new coordinator: 6
[2019-04-23 18:01:50 | 6 ] [INFO   ] Sending message to 7 : Message{type=COORDINATOR_ELECTION, srcId=6, payload=ElectionMessageHeader{electionMethod=BULLY, type=COORDINATOR, payload=CoordinatorMessage{coordinatorId=6}}}
[2019-04-23 18:01:50 | 6 ] [INFO   ] Received message: Message{type=COORDINATOR_ELECTION, srcId=5, payload=ElectionMessageHeader{electionMethod=BULLY, type=COORDINATOR, payload=CoordinatorMessage{coordinatorId=5}}}
[2019-04-23 18:01:50 | 6 ] [INFO   ] Election concluded, new coordinator: 5
[2019-04-23 18:01:50 | 6 ] [INFO   ] Received message: Message{type=COORDINATOR_ELECTION, srcId=7, payload=ElectionMessageHeader{electionMethod=BULLY, type=COORDINATOR, payload=CoordinatorMessage{coordinatorId=7}}}
[2019-04-23 18:01:50 | 6 ] [INFO   ] Election concluded, new coordinator: 7
```

Figure 17: Logs from node 6 during an election where coordinator 8 has failed, and 7 should be the next coordinator.

4 Receive/Send Posts

4.1 Mutual Exclusion

At any one time, only one server/node should be able to read or write from the message queue. In order to provide this mutual exclusion, the token-ring method was used. A token is created by the first node in the ring when initializing the network, and is forwarded around the ring after a) the node holding the token carries out a operation on the resource or b) a timeout expires.

Since only one node can have the token at any one time, mutual exclusion is ensured. No starvation can occur since the token will always eventually return to each node in the ring. The downsides of the token-ring algorithm is that the wait time between each operation grows linearly with the size of the ring. It also requires some sort of recovery mechanism if the node holding the token fails.

In order to ensure that the token is at least delivered successfully, the token acknowledgement message described earlier for detecting lost nodes was utilised. The following steps are taken between waiting on a token and forwarding it:

1. Ring message handling thread polls predecessor socket for token.

2. Client handling thread polls the single element *usableTokenQueue* waiting for the token to become available.

3. When the token arrives, the ring message thread replies with an ACK, and puts the token in the *usableTokenQueue* for the client thread to consume. It then begins polling the single element *forwardableTokenQueue* where the client thread will return the token.

4. The client thread dequeues the token from the *usableTokenQueue* and uses it to serve it's clients then returns it to ring thread via the *forwardableTokenQueue*.

5. Ring thread then removes the token from the *forwardableTokenQueue* and forwards it onto it's successor.

4.2 Server

In order for each node in the ring to serve clients, they each provide a TCP server socket. Coordination traffic and client traffic was isolated by using differenent port numbers for both. To allow for local testing, it was necessary to use port numbers to differentiate between host sockets on the same machine. In a realistic scenario, each node would have a different host address (and even a different FQDN) and a consistent port for client traffic and coordination traffic.

I had hoped to use an existing protocol such as Websockets so that the client-to-server communication followed some standard. Due to time constraints however, I opted for simply sending messages over the TCP socket, using line breaks to seperate each message. This time I serialized the messages to JSON to allow any application to consume and communicate with the server as a client, in contrast to the direct serialization of POJOs which is used for communication between nodes.

The web server consisted of a fixed size thread pool for serving up to two clients. A server socket would would wait for a client to connect, and then spin up a client handler thread for processing the new client. Clients and servers would send messages as JSON, using a newline (\n) as a delimiter for messages. Each JSON object sent included a *messageType* field with one of the values in table 4. JSON encoding and decoding was performed using the Gson library.

A publish-subscribe pattern was used for communication. Clients would send a log in message with a username so that the server knew which messages to send their way. They could also join groups which would allow for messages to be broadcast to multiple clients.

Message Type	Usage	Payload
LOGIN	Sent by client to declare a username to the node.	Username
JOIN_GROUP	Sent by client to subscribe to a group.	Name of group to join.
LEAVE_GROUP	Sent by client to unsubscribe from a group.	Name of group to leave.
CHAT_MESSAGE	Text sent between clients.	To, From, Time, Contents
ERROR	Sent by server if an error occurs	Explanation

Table 4: Messages sent between client and server.

Figure 18 shows the ER diagram of the tables added to the database in order to handle users, groups, and messages. To avoid duplicating the entire message for every member of a group, messages are inserted once, and in another table each destination for that message ID is inserted. When a message is received, the receiving server will delete the user as a recipient of the message and then delete any messages that no longer have any recipients.

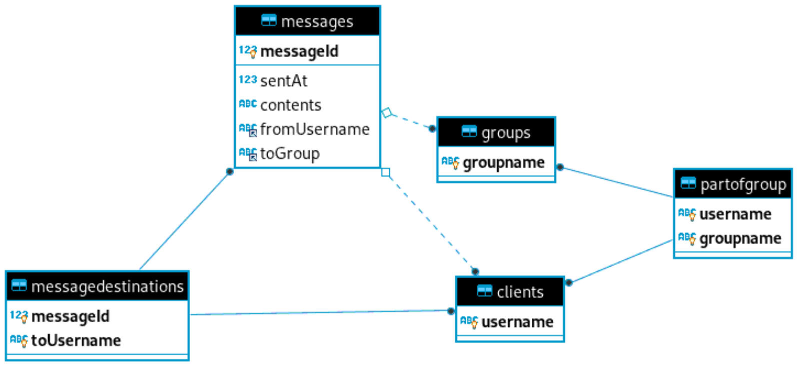
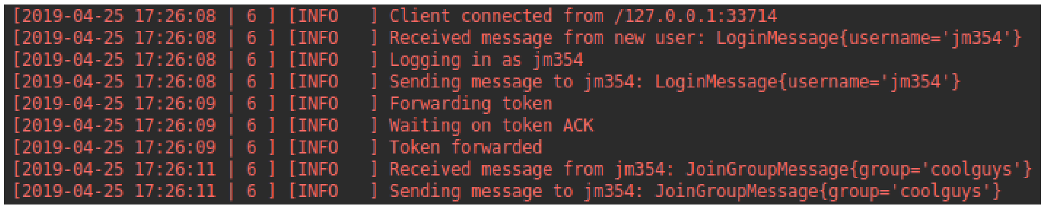


Figure 18: ER diagram for user and group messaging database.

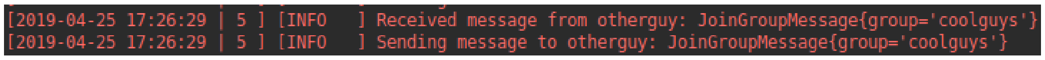
Each server is responsible for adding and removing their users to groups when requested. Once the token is available, the oldest message for any of their clients is removed from the database and forwarded to that client. The oldest message is always chosen to ensure the FIFO delivery of messages. If a user disconnects before a message reaches it, the message will remain in the database until the user connects again to any server node.

While writing the SQL queries, one of the issues I came across was using a variable number of values as part of the IN clause in a prepared statement. This was necessary for the client to fetch messages for all its users. Due to the way prepared statements are compiled and cached by the database, creating a new prepared statement for different numbers of users would reduce performance as databases typically limit the number of prepared statements cached. Alternatives included querying for each user individually (slow due to possibly high number of requests), or using binned sizes of IN lists and nulling any unused values (i.e. a different statement for 1, 3, 5 users). The best solution required knowing how many clients would be served by each server, and so with the assumption that each server would only handle two clients, a single prepared statement with two possible users in the IN clause was used.



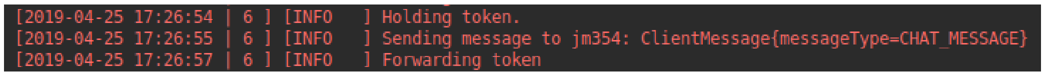
```
[2019-04-25 17:26:08 | 6 ] [INFO   ] Client connected from /127.0.0.1:33714
[2019-04-25 17:26:08 | 6 ] [INFO   ] Received message from new user: LoginMessage{username='jm354'}
[2019-04-25 17:26:08 | 6 ] [INFO   ] Logging in as jm354
[2019-04-25 17:26:08 | 6 ] [INFO   ] Sending message to jm354: LoginMessage{username='jm354'}
[2019-04-25 17:26:09 | 6 ] [INFO   ] Forwarding token
[2019-04-25 17:26:09 | 6 ] [INFO   ] Waiting on token ACK
[2019-04-25 17:26:09 | 6 ] [INFO   ] Token forwarded
[2019-04-25 17:26:11 | 6 ] [INFO   ] Received message from jm354: JoinGroupMessage{group='coolguys'}
[2019-04-25 17:26:11 | 6 ] [INFO   ] Sending message to jm354: JoinGroupMessage{group='coolguys'}
```

Figure 19: Logs from client connecting and logging in, and then joining a group.



```
[2019-04-25 17:26:29 | 5 ] [INFO   ] Received message from otherguy: JoinGroupMessage{group='coolguys'}
[2019-04-25 17:26:29 | 5 ] [INFO   ] Sending message to otherguy: JoinGroupMessage{group='coolguys'}
```

Figure 20: Other user connected to other node joining same group as user in figure 19



```
[2019-04-25 17:26:54 | 6 ] [INFO   ] Holding token.
[2019-04-25 17:26:55 | 6 ] [INFO   ] Sending message to jm354: ClientMessage{messageType=CHAT_MESSAGE}
[2019-04-25 17:26:57 | 6 ] [INFO   ] Forwarding token
```

Figure 21: Messages only being sent to user once the server holds the token.

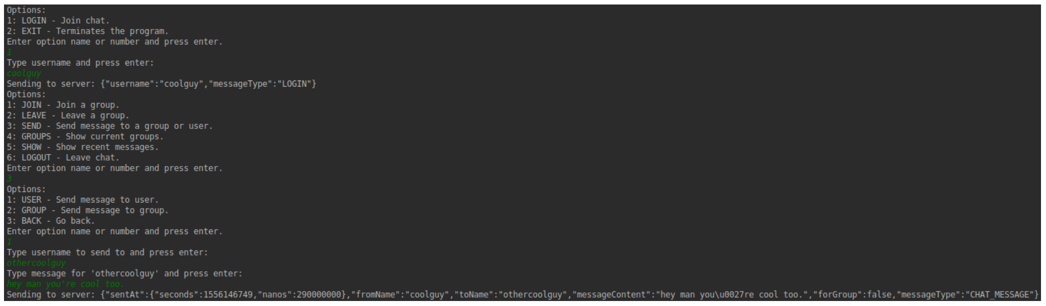
4.3 Client (RingChat)

The client UI is a simple command line interface, though an interface was enforced for the UI class to allow for other implementations. The client application takes the address and port number of the server it is to connect to in the ring as arguments.

The user is able to login, join and leave groups, send messages to other users and groups, and read messages for them. Asynchronous communication is used, and so when requesting to join or leave a group the server may immediately reply with confirmation. The client can be started by following the instructions in table 5.

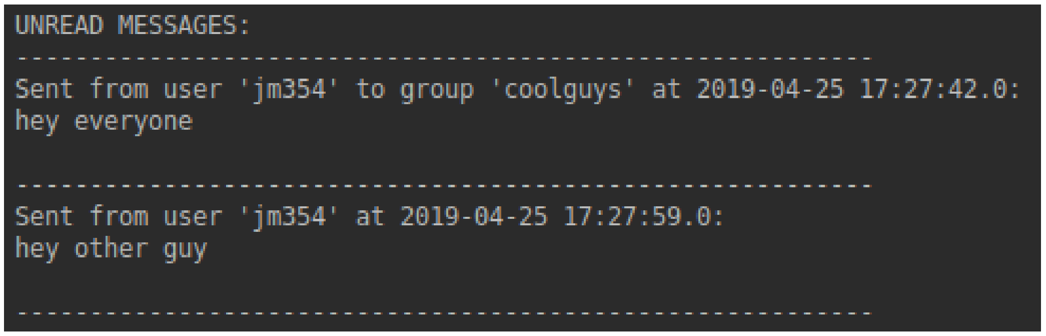
5 Testing

Only some JUnit tests were written during development. Since components were changed many times over the course of this practical, tests were con-



```
Options:
1: LOGIN - Join chat.
2: EXIT - Terminates the program.
Enter option name or number and press enter.
1
Type username and press enter:
coolguy
Sending to server: {"username":"coolguy","messageType":"LOGIN"}
Options:
1: JOIN - Join a group.
2: LEAVE - Leave a group.
3: SEND - Send message to a group or user.
4: GROUPS - Show current groups.
5: SHOW - Show recent messages.
6: LOGOUT - Leave chat.
Enter option name or number and press enter.
3
Options:
1: USER - Send message to user.
2: GROUP - Send message to group.
3: BACK - Go back.
Enter option name or number and press enter.
1
Type username to send to and press enter:
othercoolguy
Type message for 'othercoolguy' and press enter:
hey man you're cool too.
Sending to server: {"sentAt":{"seconds":1556146749,"nanos":290000000},"fromName":"coolguy","toName":"othercoolguy","messageContent":"hey man you\u0027re cool too.","forGroup":false,"messageType":"CHAT_MESSAGE"}
```

Figure 22: Example of a user logging in and sending a message to another user using the CLI.



```
UNREAD MESSAGES:
-----------------------------------------------------
Sent from user 'jm354' to group 'coolguys' at 2019-04-25 17:27:42.0:
hey everyone

-----------------------------------------------------
Sent from user 'jm354' at 2019-04-25 17:27:59.0:
hey other guy

-----------------------------------------------------
```

Figure 23: Messages received by user 'otherguy'. Both a group message and direct message can be seen.

usage: java -jar ⟨program⟩-with-dependencies.jar

hostname	Address of server node to connect to.
hostport	Port on server to connect to.

Table 5: Arguments for running client.

stantly being rewritten and so were eventually abandoned. Given more time I would have unit tested each component by mocking network messages.

However, the project was tested thoroughly by hand as it was developed which helped identify edge cases like those discussed. The ring topology was tested by starting and triggering failure of nodes and observing the logs and database state to ensure that such events were handled correctly. The client was also tested by sending messages to users and groups, attempting to connect to a server that was already handling two clients, and so on.

6 Potential Issues

Issues with the implementation:

1. Messages between nodes are serialzed POJOs, which would make it difficult to monitor message passing using another application, or adding an implementation of the ring server in another language.
2. If a server stalls rather than fails, it will be treated as failed by its surrounding nodes, and recovery for the stalling node is not ensured unless it is restarted.
3. Clients have to connect to a specific server. Could be avoided by implementing another service to provide clients with a server to connect to, which could provide load balancing.
4. All server addresses have to be known on startup. Since the addresses are stored in a database however, it would be possible to add a mechanism for introducing new nodes.
5. No acknowledgements or retry mechanisms exist for election messages, only for token passing.
6. No read/delivery reciepts for clients.
7. If failing node was holding token, token is lost and no recovery mechanism exists.
8. Bully algorithm uses seperate UDP message when broadcasting coordinator message, when multicast would be more effecient in terms of network traffic.
9. Lack of unit testing.

7 Summary

Functionalities implemented:

1. Dynamic ring formation
2. Recovery from node loss
3. Recovery from coordinator loss
4. Multiple methods of coordinator election.
5. Ensured token delivery
6. Database connection using transactions for resources P and Q.
7. Mutual exclusion using token-ring algorithm.
8. CLI for clients to send and receive messages, and login and join groups.
9. Multicast communication using group membership.

This practical was very enjoyable to work on. It greatly improved my understanding and ability to design distributed systems. Given more time I would have liked to tackle the issues discussed and introduce a GUI rather than the CLI, but the CLI was enough to demonstrate that the token ring mutual exclusion and token passing functionalities worked whilst still being fairly user friendly.

8 How to Run

Both the server nodes and client are provided as a executable jar file, and these jars can be built by using mvn clean install whilst in the directory of the pom.xml files. The jar file with dependencies should be used.

The arguments required for both are provided in the relevant sections. The database server connection URL and credentialy is that of the databases provided by the school. The first node to start up should be provided with the −d flag in order to restart the database and clear any previous coordinators.

References

[1] Apache. Apache maven project. `https://maven.apache.org/`.

[2] Apache Commons. Apache commons cli. `https://commons.apache.org/proper/commons-cli/`.

[3] D. Lee, A. Puri, P. Varaiya, R. Sengupta, R. Attias, and S. Tripakis. A wireless token ring protocol for ad-hoc networks. In *Proceedings, IEEE Aerospace Conference*, volume 3, pages 3–3, March 2002.