Reconfigurable Replicated State Machine

Seif Haridi

KTH

Motivation

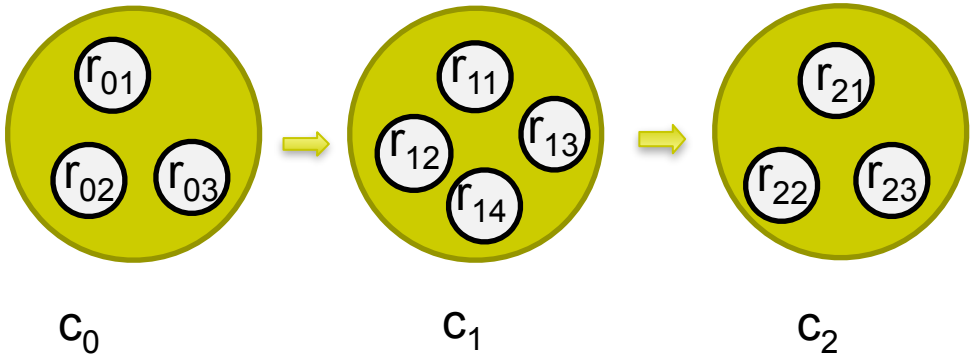
- A Replicated State Machine (RSM) is running on a set of N processes (typically 3 or 5)
- Can tolerate up to $\lfloor N/2 \rfloor$ process failures
  - One more and RSM unavailable
  - Need a way to replace faulty processes
- Impossible to know if a process is faulty or slow in asynchronous system
  - Must be able to replace any process,
  - This is called reconfiguration

Policy (when) vs Mechanism (how)

- External agent decides when to reconfigure
  - Autonomous management system
  - Or human operator
- The agent chooses new configuration
  - Example: $\Pi_{old}=\{p_1,p_2,p_3\} \Rightarrow \Pi_{new}=\{p_1,p_2,p_4\}$
    - Can, in general, be a completely new set of processes
      - $\Pi_{old} \cap \Pi_{new} = \varnothing$
    - Often a single suspected process is replaced
- Only concerned with mechanism
  - Leave the policy as open and flexible as possible

Configurations

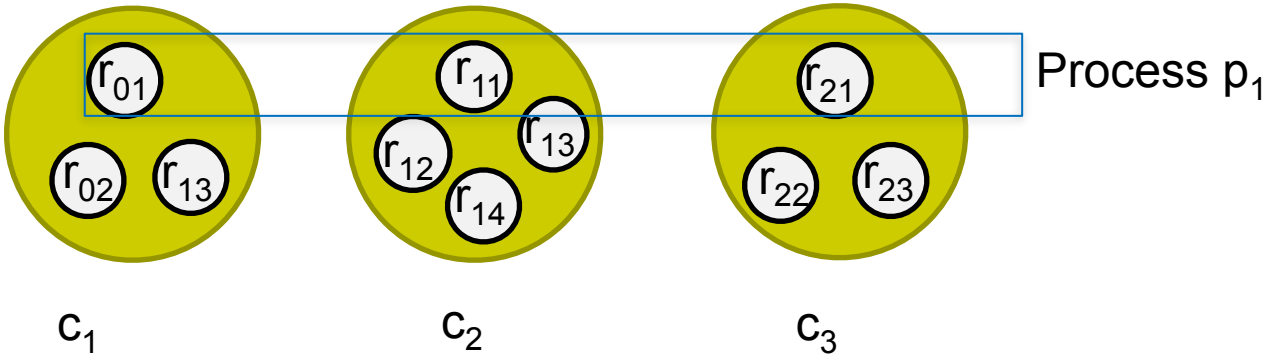
- Each configuration is conceptually an instance of Sequence-Paxos



- Replicas in configuration $c_0 = \{r_{01}, r_{02}, r_{03}\}$
- A process p1 may act as multiple replicas
  - In different configurations, for example $\{r_{01}, r_{11}, r_{21}\}$

Configurations

- Each configuration is conceptually an instance of Sequence-Paxos



- Replicas in configuration $c_1 = \{r_{11}, r_{12}, r_{13}, r_{14}\}$
- A process may act as multiple replicas In different configurations,
  - for example p1 is $\{r_{01}, r_{11}, r_{21}\}$

Configurations

- RSM executes in a configuration until a reconfiguration occurs, then moves to new configuration
  - Processes that move to the new configuration from the previous one does that asynchronously
  - Once a majority of processes have moved/entered the new configuration is **active**
- The first configuration, c_0, starts with the empty sequence accepted in round 0
- It then runs normally
  - If sequence v is issued in round n then v is an extension of all sequences chosen in rounds ≤ n

Ballot Array of c_0

- Replicas $r_{0,1}$, $r_{0,2}$ and $r_{0,3}$ in configuration c_0

$\mathcal{R}_{i,j}$ *replica j in config i*

Round	Accepted by $r_{0,1}$	Accepted by $r_{0,2}$	Accepted by $r_{0,3}$
…			
n=2		$\langle C_2 \rangle$	$\langle C_2 \rangle$
n=1	$\langle C_1 \rangle$		
n=0	$\langle\rangle$	$\langle\rangle$	$\langle\rangle$

- Empty sequence accepted in round 0
- If sequence v is issued in round n then v is an extension of all sequences chosen in rounds ≤ n

Stop-sign in c_0

- At some point, a special *stop-sign* command is proposed, and a proposer extends the current sequence with this command
- The sequence with the *stop-sign* as last command is the *final sequence in* c_0
- No sequence longer than the final sequence in c_0 may be issued by any proposer in c_0
- Therefore, after the final sequence is chosen, no longer sequence can be chosen in c_0, and c_0 is *stopped*

Final Sequence in c_0

- Replicas $r_{0,1}$, $r_{0,2}$ and $r_{0,3}$ in configuration c_0

Round	Accepted by $r_{0,1}$	Accepted by $r_{0,2}$	Accepted by $r_{0,3}$
…	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$
n=3	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$
n=2		$\langle C_2 \rangle$	$\langle C_2 \rangle$
n=1	$\langle C_1 \rangle$		
n=0	$\langle\rangle$	$\langle\rangle$	$\langle\rangle$

- SS_0 is the stop-sign command in c_0
- The final sequence in c_0 is $\sigma_0 = \langle C_2, SS_0 \rangle$
- Any Sequence in rounds n > 3 will be σ_0

Final Sequence in c_0

- Replica $r_{0,1}$ and p_1 crashed at round 3 after σ_0 is chosen, $r_{0,2}$ or $r_{0,3}$ proposes

Round	Accepted by $r_{0,1}$ at p_1	Accepted by $r_{0,2}$ at p_2	Accepted by $r_{0,3}$ at p_3
…		$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$
n=3	$\langle C_2, SS_0 \rangle$		$\langle C_2, SS_0 \rangle$
n=2		$\langle C_2 \rangle$	$\langle C_2 \rangle$
n=1	$\langle C_1 \rangle$		
n=0	$\langle \rangle$	$\langle \rangle$	$\langle \rangle$

- The final sequence in c_0 is $\sigma_0 = \langle C_2, SS_0 \rangle$
- Eventually all correct replicas has decided on SS_0

Starting New Configurations

Starting a New Configuration

- Once the final sequence (v_a) is decided σ_i in c_i and is in the persistent store by **one process** p the new configuration c_{i+1} can start
  - C_i is stopped
- SS_i has complete information about the c_{i+1}
  - Π_{i+1} : the set of processes in c_{i+1}
  - cfg : new configuration number
  - RID: for each process p_j in Π_{i+1} its replica identifier $r_{i+1,j}$
- Each correct p_j that is in both in c_i and c_{i+1} waits for its replica $r_{i,j}$ to decide its final sequence σ_i before taking it over as its initial sequence
- Each correct p_j not in c_i copies its initial sequence σ_i from persistent store

Starting a New Configuration

- Each process p_j starts its new replica in c_{i+1}
- For each replica, the final sequence in c_i is automatically accepted in round 0 of c_{i+1}
  - Round 0 in each configuration is special
  - Other rounds work as normal
- In leader-based consensus each configuration has its own leader election abstraction
- the leader election abstraction starts when the new configuration starts

Initial Sequence in c_1

- Replicas $r_{1,1}$, $r_{1,2}$ and $r_{1,4}$ in configuration c_1

Round	Accepted by $r_{1,1}$ at p_1	Accepted by $r_{1,2}$ at p_2	Accepted by $r_{1,4}$ at p_4
…			
n=3			
n=2			
n=1			
n=0	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$

- The final sequence in c_0 is chosen in round 0 in configuration c_1
- P_3 is removed

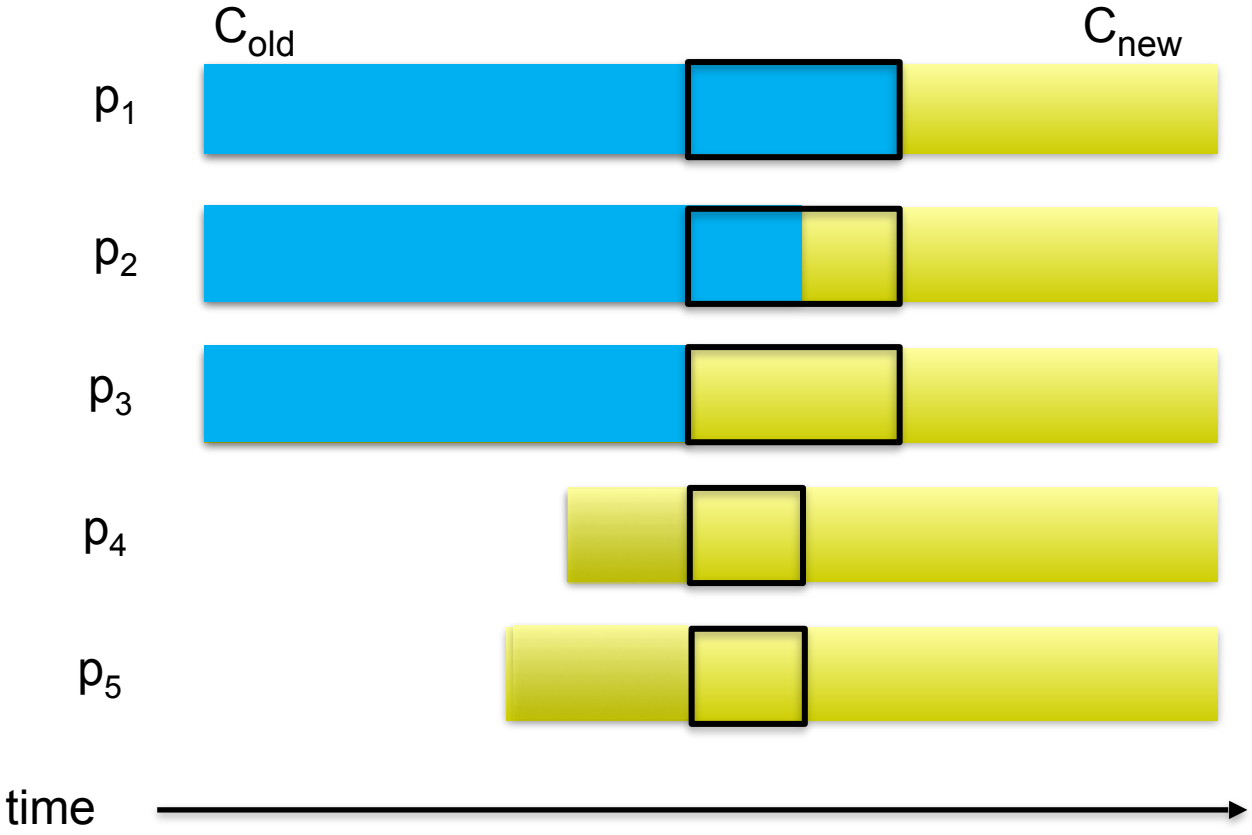
Execution in c_1

- Replicas $r_{1,1}$, $r_{1,2}$ and $r_{1,4}$ in configuration c_1

Round	Accepted by $r_{1,1}$ at p_1	Accepted by $r_{1,2}$ at p_2	Accepted by $r_{1,4}$ at p_4
…			
n=3	$\langle C_2, SS_0, C_3, C_5 \rangle$	$\langle C_2, SS_0, C_3, C_5 \rangle$	
n=2			$\langle C_2, SS_0, C_3, C_4 \rangle$
n=1	$\langle C_2, SS_0, C_3 \rangle$	$\langle C_2, SS_0, C_3 \rangle$	$\langle C_2, SS_0, C_3 \rangle$
n=0	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$

- The final sequence in c_0 is chosen in round 0 in configuration c_1

Overlapping configurations



Extend Round Numbers

- Round numbers are extended to pairs (c, n)
  - c is a configuration and n is local round number within that configuration
- Since configurations are totally ordered, rounds are totally ordered across configurations

Ordering Rounds Totally

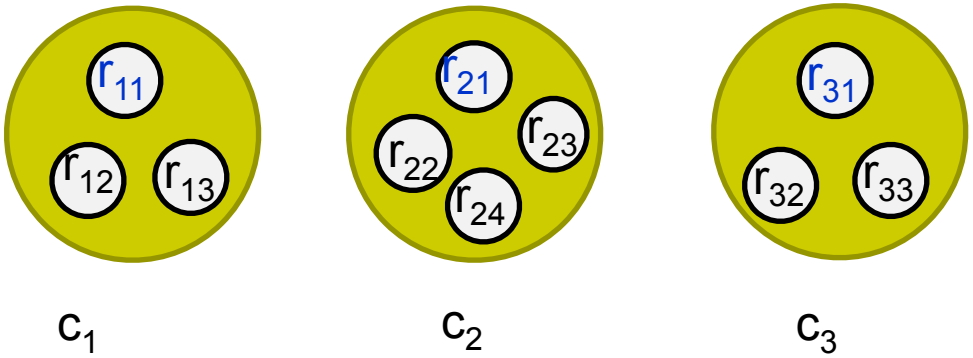
Round	Accepted by $r_{c1,1}$	Accepted by $r_{c1,2}$	Accepted by $r_{c1,4}$
…			
n=(c_1, 3)	$\langle C_2, SS_0, C_3, C_5 \rangle$	$\langle C_2, SS_0, C_3, C_5 \rangle$	
n=(c_1, 2)			$\langle C_2, SS_0, C_3, C_4 \rangle$
n=(c_1, 1)	$\langle C_2, SS_0, C_3 \rangle$	$\langle C_2, SS_0, C_3 \rangle$	$\langle C_2, SS_0, C_3 \rangle$
n=(c_1, 0)	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$
Round	**Accepted by $r_{c0,1}$**	**Accepted by $r_{c0,2}$**	**Accepted by $r_{c0,3}$**
…	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$
n=(c_0, 3)	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$	$\langle C_2, SS_0 \rangle$
n=(c_0, 2)		$\langle C_2 \rangle$	$\langle C_2 \rangle$
n=(c_0, 1)	$\langle C_1 \rangle$		
n=(c_0, 0)	$\langle\rangle$	$\langle\rangle$	$\langle\rangle$

Starting/Stopping Configuration

- A process have replicas in multiple configurations
  - But can only be ***running*** in **one** configuration at any time
- Starting and stopping configuration c_i is not coordinated between processes
  - process pi may have a stopped replica at c_{i-1} helping other replicas to reach the final sequence in c_{i-1}
  - process pi may have a replica in c_{i+1} that did not start yet

Configurations

- Each configuration is conceptually an instance of Sequence-Paxos



- A process p may act as multiple replicas
  - in different configurations, for example $\{r_{11}, r_{21}, r_{31}\}$
  - p is stopped in c_1 , running in c_2 , not-started in c_3

Hand-Over

- As soon as proposer p in c_i learns that the final sequence σ_i in c_i is chosen, p should inform replicas in c_{i+1} about σ_i
  - So that replicas in c_{i+1} can start, to maintain availability
- Process that acts as replica in both c_i and c_{i+1} will learn σ_i through normal Decide msgs
- Other replicas in c_{i+1} must also learn σ_i
  - Send additional Decide messages

Optimizations

Hand-Over: Early Sequence Transfer

- As leader p receives proposal with stop-sign command SS, one possibility is for p to not issue proposal with SS immediately
- Instead, p starts to update replicas in c_{i+1} with longest sequence decided so far
- Only sends accepts SS once replicas in c_{i+1} are sufficiently up to date
- This way the interruption in service is minimized
  - Trade-offs

Efficient Hand-Over

- If new replica process p is introduced in system then entire sequence has to be transferred to p
  - This may take some time
- Dividing the sequence into chunks, and letting other processes in the same configuration send chunks in parallel to p may increase efficiency
  - Trade-off between on network capacity, processor load, etc.

Snapshots

- Currently, the entire sequence of commands must be transferred from a configuration to the next specially when new processes are introduced
- It is possible to take a snapshot of the state of the state machine after it has executed a certain number of commands
  - E.g. every 1000 commands or every 1h
  - Can then garbage collect prefix of sequence
- Care must be taken to still prevent duplicate commands?

Prepare Phase

- A leader p in c_i sends Prepare messages to all replicas in c_i
- For each process q , there are three cases:
  1. q's replica is running in c_i: q behaves normally
  2. q's replica hasn't started in c_i yet: q obtains final sequence in c_{i-1} from p, starts its replica in c_i, and sends Promise to p
  3. q's replica has stopped c_i: q sends the final sequence in c_i to p, after which p will also stop and starts its replica in c_{i+1}
- In case 1 and 2, p waits for Promise messages from a majority

Summary

- Reconfiguring a replicated state machine is relatively straight forward
- Round numbers are extended so that rounds in an earlier configuration are ordered before rounds in a later configuration
- At most one of the replicas that a process implements may be running at any time
- The hand-over procedure is important in order to get availability and efficiency