Lecture 19: Fault Tolerance, Group Communication and Replicated State Machines

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Basic Concepts & Definitions

- **Fault tolerance** is the ability of a system to continue operating in the presence of faults
- Closely-related to requirements on dependable systems
  - Availability: probability that system is working correctly at any given time
  - Reliability: probability that system can run continuously without failure
  - Safety: temporary faults do not lead to catastrophic failures
  - Maintainability: ease of repairing a failed system

Avoiding faults

- All of the standard coping with complexity stuff
  - software engineering, testing, etc...
- There are also some design "rules" that can help
  - Example: avoid situations in which things often go wrong
    - 90% utilization of file system capacity
    - minimum number of free pages
  - Example: regular maintenance
    - planned restarts: occasionally reset to clean state
    - patches/upgrades: don't leave known problems laying around
  - Example: detect problematic activity at system boundary
    - firewalls for blocking suspect traffic
- Note that this *reduces* rather than *prevents* problems

Masking/hiding faults

- Obvious requirement: redundancy
  - Must be able to repair broken sets of bits
    - e.g., error correction codes
  - Must be able to communicate despite broken paths
    - e.g., redundant routes, dual ported devices, etc...
  - Must be able to continue with broken servers
    - e.g., have more than one server providing same service
  - Requires *group communication* → distributed consensus
Recovering from faults

- Many systems are designed to tolerate a single fault
  - Must detect and recover before a second fault occurs
  - Generalizes to tolerating $f$ faults, recovering before fault $f+1$ occurs
- In general, requires restoring state of restarted process or service
  - Checkpointing: save state to stable storage
  - Replicated state machines: rebuild state from other group members

Replicated State Machines (RSMs)

- Architecture
  - Implement a service as a state machine
    - State variables
    - Commands
  - Replicate the state machine on different servers
  - Clients interact with sets of servers
- Rationale
  - Fault-tolerance/Availability/Reliability

State Machine Commands

- A message that the state machine receives
- Commands must execute atomically with respect to other commands
  - Referred to as 'linearizability'
- Commands
  - Modify state variables
  - Produce outputs
- The state/output of a state machine is completely determined by:
  - initial state
  - sequence of commands

RSMs & Failures

- In the case of failures
  - Clients must determine correct output of RSMs
  - RSMs are called $t$-tolerant
    - Fail-stop: $t + 1$ replicas required ($I$ correct replica sufficient)
    - Byzantine: $2t + 1$ replicas required ($t + 1$ correct replicas sufficient)
  - Different than Broadcast/Consensus failures
    - One client must decide on result, replicas don’t have to agree with each other about result
**RSMs, Consensus & Reliable Broadcast**

- Each correct replica
  - Must execute same commands in same order
  - Since all correct replicas must have the same state
- Therefore, RSMs require Distributed Consensus to agree on order of commands
- Needs form of group communication called atomic broadcast

**Group communication**

- In many applications processes must be able to reliably broadcast messages, so that they agree on the set of messages they deliver.
- Reliable broadcast is difficult because distributed processes do not know each other’s state.
- Much of this material is taken from chapter five by Hadzilacos and Toueg in “Distributed Systems”, Sape Mullender, ed.
- Reliable broadcast taxonomy
- Example broadcast algorithms

**Application / Broadcast Mechanism**

<table>
<thead>
<tr>
<th>Application Protocol</th>
<th>Broadcast Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>broadcast(m)</td>
<td>send(m)</td>
</tr>
<tr>
<td>deliver(m)</td>
<td>receive(m)</td>
</tr>
</tbody>
</table>

**Properties of Send/Receive**

- **Validity:** If \( p \) sends \( m \) to \( q \), and both \( p \) and \( q \) and the link between them are correct, then \( q \) eventually receives \( m \).

- **Uniform Integrity:** For any message \( m \), \( q \) receives \( m \) at most once from \( p \), and only if \( p \) previously sent \( m \) to \( q \).

- E.g. Communication with TCP
Properties of Broadcast/Deliver

- **Validity**: If a correct process broadcasts a message \( m \), then all correct processes eventually deliver \( m \).
- **Agreement**: If a correct process delivers a message \( m \), then all correct processes eventually deliver \( m \).
- **Integrity**: For any message \( m \), every correct process delivers \( m \) at most once, and only if \( m \) was previously broadcast by \( \text{sender}(m) \).

Message Order

- **Unordered**: no guarantees on delivery order
- **FIFO Order**: If a process broadcasts a message \( m \) before it broadcasts a message \( m' \), then no correct process delivers \( m' \) unless it has previously delivered \( m \).
- **Causal Order**: If the broadcast of a message \( m \) causally precedes the broadcast of a message \( m' \), then no correct process delivers \( m' \) unless it has previously delivered \( m \).
- **Total Order**: All correct processes deliver messages in the same order
  - May be combined with any of the above delivery constraints

Broadcast Taxonomy

- **Reliable Broadcast**
  - **Total Order**
  - **Atomic Broadcast**
- **FIFO Broadcast**
  - **Total Order**
  - **FIFO Atomic Broadcast**
- **Causal Broadcast**
  - **Total Order**
  - **Causal Atomic Broadcast**

Reliable Broadcast Alg. (Diffusion)

Every process \( p \) executes:

```csharp
// to reliably broadcast messages
void ReliableBroadcast(m) {
    // make m unique
tag m with sender(m), sequence_number(m)
send(m) to all neighbors including p
}

// event loop for receive events
upon receive(m) do
    if p has not previously executed ReliableDeliver(m) then
        if sender(m) ≠ p
            then
                send(m) to all neighbors
                ReliableDeliver(m)
```
“Diffusion” Algorithm Considered

- Works in synchronous or asynchronous system
- Assumes network does not partition
- Failures assumed to be fail-stop
- Floods the network
  - especially if processes are highly connected

FIFO Broadcast Algorithm

- FIFO Algorithm is layered on top of Reliable Broadcast
- Each process $p$ maintains, for each other process $q_i$, the next sequence number it can FIFODeliver
- Buffers ReliableDelivered messages until the sequence number indicates message may be FIFODelivered

Causal Broadcast Algorithm

- Causal algorithm is layered on top of FIFO alg.
- CausalBroadcast prepends list of messages upon which $m$ causally depends then calls FIFOBroadcast
- Dependent messages is the list of messages CausalDelivered since last CausalBroadcast.
- Buffers FIFODelivered messages until all messages upon which $m$ depends have been CausalDelivered.

Broadcast Taxonomy

- Reliable Broadcast $\rightarrow$ Total Order $\rightarrow$ Atomic Broadcast
- FIFO Order $\rightarrow$ FIFO Order
- FIFO Broadcast $\rightarrow$ Total Order $\rightarrow$ FIFO Atomic Broadcast
- Causal Order $\rightarrow$ Total Order $\rightarrow$ Causal Atomic Broadcast
Atomic Broadcast

- Atomic Broadcast is a form of Distributed Consensus
  - Therefore no deterministic, asynchronous algorithm
  - Synchronous algorithms for various failure models exist
- Other Atomic Broadcast algorithms can be built on top of Atomic Broadcast with similar limitations
  - FIFO Atomic Broadcast
  - Causal Atomic Broadcast

Schneider Tutorial on RSMs

- Not distinguished for clarity of assumptions/model of failure and synchrony
  - But better than any other paper as an introduction to RSMs
- Ties together:
  - Broadcast, consensus,
  - logical clocks, clock synchronization
  - leases, heartbeats, failure detectors,
  - group membership (reconfiguration),
  - recovery (managing configuration)

Another Viewpoint/Approach

- Distributed Consensus
  - Servers communicate amongst themselves to reach agreement on state.
- Reliable Broadcast
  - Servers communicate amongst themselves to order messages
- What can clients do?
  - Clients can read and write to sets of servers in a consistent manner
  - Storing/restoring the state variables to servers & implementing a state machine locally is similar to RSMs

Voting

- Let V be the number of votes in the system
- Let W be the number of votes required to write
- Let R be the number of votes required to read
- Overlap Constraint:
  - \( R + W > V \)
  - Recommend:
    - \( 2 \times W > V \)
    - \( R + W < V + \varepsilon \)
- Data must contain a version number or timestamp
- If constraints are met, then data will remain consistent.
- Note that votes can be arbitrarily assigned to servers in the system (i.e. weights can be assigned to servers)
Quorums

- Quorums are a generalization of voting.
  - Organize servers into logical structures.
- Overlap constraint
  - Every write quorum must overlap with every read quorum
  - Example: writes must go to a column, reads must get a row.
- Note that voting does not imply majority