Plan for Today

- More on fault tolerance in distributed systems
- Techniques for scalability
- Consistency models
- Importance of Openness & Flexibility

Fault Tolerance Terminology

- Distributed systems should tolerate partial failure
- Faults cause errors that lead to failure
- Aspects of dependability:
  - Availability
  - Reliability
  - Safety
  - Security
  - Maintainability
- Types of faults:
  - Transient vs. intermittent vs. permanent

Failure Models

<table>
<thead>
<tr>
<th>Type of failure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crash failure</td>
<td>A server halts, but is working correctly until it halts</td>
</tr>
<tr>
<td></td>
<td>Fail-Stop: if this can be detected</td>
</tr>
<tr>
<td></td>
<td>Fail-Silent: if not (and others may wrongly believe in crash)</td>
</tr>
<tr>
<td>Omission failure</td>
<td>A server fails to respond to incoming requests</td>
</tr>
<tr>
<td>Receive omission</td>
<td>A server fails to receive incoming messages</td>
</tr>
<tr>
<td>Send omission</td>
<td>A server fails to send messages</td>
</tr>
<tr>
<td>Timing failure</td>
<td>A server’s response lies outside the specified time interval</td>
</tr>
<tr>
<td>Response failure</td>
<td>The server’s response is incorrect</td>
</tr>
<tr>
<td>Value failure</td>
<td>The value of the response is wrong</td>
</tr>
<tr>
<td>State transition failure</td>
<td>The server deviates from the correct flow of control</td>
</tr>
<tr>
<td>Arbitrary failure</td>
<td>A server may produce arbitrary responses at arbitrary times</td>
</tr>
</tbody>
</table>

Types of Redundancy

- Redundancy masks failures
- Information Redundancy:
  - Example: Forward Error Correction (FEC)
- Time Redundancy:
  - Example: Transactions
- Physical Redundancy:
  - Example: Triple Modular Redundancy
- Let’s look at redundancy through replication
Types of Replication Protocols

- Primary-based protocols
  - hierarchical group
  - generally primary-backup protocols
  - options for primary:
    - may propagate notifications, operations, or state
- Replicated-write protocols
  - flat group using distributed consensus

Election Algorithms

- For primary-based protocols, elections are necessary
- Need to select one “coordinator” process/node from several candidates
  - All processes should agree
- Use logical numbering of nodes
  - Coordinator is the one with highest number
- Two brief examples:
  - Bully algorithm
  - Ring algorithm

Bully Algorithm (1)

Bully Algorithm (2)

Ring Algorithm
K fault tolerance (in Repl. Write)

- A system is *k*-fault tolerant if it can tolerate faults in *k* components and still function.
- Many results known; strongly dependent on assumptions:
  - Whether message delivery is reliable
  - Whether there is a bound on msg delivery time
  - Whether processes can crash and in what way:
    - Fail-stop, silent-fail or Byzantine

Reliable Communication

- Critical: without it, no agreement is possible
- Aka “Two Army Problem”
  - Two armies must agree on a plan to attack, but don't have reliable messengers to inform each other
  - Assumes that armies are loyal (=processes don’t crash)
- Hence all consensus is only as reliable as protocol used to ensure reliable communication
- Aside: in networking, causes corner case on TCP close

Byzantine Agreement in Asynchronous Systems

- Asynchronous:
  - Assumes reliable message transport, but with possibly unbounded delay
- Agreement is impossible with even one faulty process. Why?
  - Proof: Fischer/Lynch/Paterson 1985
  - Decision protocol must depend on single message:
    - Delayed: wait for it indefinitely
    - Or declare sender dead: may get wrong result

Alternatives

- Sacrifice safety, guarantee liveness
  - Might fail, but will always reply within bounds
- Guarantee liveness probabilistically
  - “Probabilistic Consensus”
  - See also “weak synchrony” assumption in Castro paper
  - Allow for protocols that may never terminate; but this would happen w/ probability zero
    - E.g., always terminates, but impossible to say when in the face of delay

K-Fault Tolerance Conditions

- To provide K-fault tolerance for 1 client with replicated servers
  - Need *k*+1 replicas if at most *k* can fail silent
  - Need 2*k*+1 replicas if up to *k* byzantine failures and all respond (or fail stop)
  - Need 3*k*+1 replicas if up to *k* byzantine failures and replies can be delayed
  - Optimal: both necessary and sufficient

Virtual Synchrony

- Recall: for replication to make sense, all replicas must perform same set of operations
  - Generalization: “replicated state-machines”
- Virtual Synchrony:
  - Definition: A message is either delivered to all processes in a group or to none
  - Keyword: *delivered* (vs. received)
Message Receipt vs. Delivery

Virtual Synchrony (cont’d)

- Observation: ensuring virtual synchrony requires agreement on group membership
- Group membership can change:
  - Processes may leave/crash
  - Processes may join/restart
- Idea: associate message m with current Group View (set of receivers)

Virtual Synchrony & Views

Atomic Multicast

= Virtual Synchrony + Total-order Delivery

Classification of virtual synchronous reliable multicasting:

<table>
<thead>
<tr>
<th>Message Ordering</th>
<th>None</th>
<th>FIFO Ordering</th>
<th>Causal Ordering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not total-ordered</td>
<td>Reliable Multicast</td>
<td>FIFO Multicast</td>
<td>Causal Multicast</td>
</tr>
<tr>
<td>Total-ordered</td>
<td>Atomic Multicast</td>
<td>FIFO Atomic Multicast</td>
<td>Causal Atomic Multicast</td>
</tr>
</tbody>
</table>

Summary Fault Tolerance

- Fault tolerance in replicated write systems requires:
  - Distributed consensus
  - Which assumes atomic multicast, which must solve two subproblems
    - Virtually synchronous: same set of msg
    - Totally ordered: same order