Today: Fault Tolerance

- Agreement in presence of faults
  - Two army problem
  - Byzantine generals problem
- Reliable communication
- Distributed commit
  - Two phase commit
  - Three phase commit
- Paxos
- Failure recovery
  - Checkpointing
  - Message logging
Fault Tolerance

- Single machine systems
  - Failures are all or nothing
    - OS crash, disk failures

- Distributed systems: multiple independent nodes
  - Partial failures are also possible (some nodes fail)

- **Question:** Can we automatically recover from partial failures?
  - Important issue since probability of failure grows with number of independent components (nodes) in the systems
  - $\text{Prob}(\text{failure}) = \text{Prob}(\text{Any one component fails}) = 1 - \text{Prob}(\text{no failure})$
A Perspective

- Computing systems are not very reliable
  - OS crashes frequently (Windows), buggy software, unreliable hardware, software/hardware incompatibilities
  - Until recently: computer users were “tech savvy”
    - Could depend on users to reboot, troubleshoot problems
  - Growing popularity of Internet/World Wide Web
    - “Novice” users
    - Need to build more reliable/dependable systems
  - Example: what is your TV (or car) broke down every day?
    - Users don’t want to “restart” TV or fix it (by opening it up)
- Need to make computing systems more reliable
  - Important for online banking, e-commerce, online trading, webmail…
Basic Concepts

• Need to build *dependable* systems

• Requirements for dependable systems
  – Availability: system should be available for use at any given time
    • 99.999 % availability (five 9s) => very small down times
  – Reliability: system should run continuously without failure
  – Safety: temporary failures should not result in a catastrophic
    • Example: computing systems controlling an airplane, nuclear reactor
  – Maintainability: a failed system should be easy to repair
Basic Concepts (contd)

• Fault tolerance: system should provide services despite faults
  – Transient faults
  – Intermittent faults
  – Permanent faults
## 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>Omission failure</td>
<td>- Receive omission</td>
</tr>
<tr>
<td></td>
<td>A server fails to respond to incoming requests</td>
</tr>
<tr>
<td></td>
<td>- Send omission</td>
</tr>
<tr>
<td></td>
<td>A server fails to receive incoming messages</td>
</tr>
<tr>
<td></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></td>
<td>- Value failure</td>
</tr>
<tr>
<td></td>
<td>The value of the response is wrong</td>
</tr>
<tr>
<td></td>
<td>- State transition failure</td>
</tr>
<tr>
<td></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>

- Different types of failures.
Failure Masking by Redundancy

(a)

(b)

• Triple modular redundancy.
Agreement in Faulty Systems

• How should processes agree on results of a computation?
• *K-fault tolerant*: system can survive k faults and yet function
• Assume processes fail silently
  – Need (k+1) redundancy to tolerate k faults
• *Byzantine failures*: processes run even if sick
  – Produce erroneous, random or malicious replies
    • Byzantine failures are most difficult to deal with
  – Need ? Redundancy to handle Byzantine faults
Byzantine Faults

• Simplified scenario: two perfect processes with unreliable channel
  – Need to reach agreement on a 1 bit message
• Two army problem: Two armies waiting to attack
  – Each army coordinates with a messenger
  – Messenger can be captured by the hostile army
  – Can generals reach agreement?
  – Property: Two perfect process can never reach agreement in presence of unreliable channel
• Byzantine generals problem: Can N generals reach agreement with a perfect channel?
  – M generals out of N may be traitors
Byzantine Generals Problem

Recursive algorithm by Lamport

The Byzantine generals problem for 3 loyal generals and 1 traitor.

a) The generals announce their troop strengths (in units of 1 kilosoldiers).
b) The vectors that each general assembles based on (a)
c) The vectors that each general receives in step 3.
Byzantine Generals Problem Example

The same as in previous slide, except now with 2 loyal generals and one traitor.

Property: With $m$ faulty processes, agreement is possible only if $2m+1$ processes function correctly out of $3m+1$ total processes. [Lamport 82]

- Need more than two-thirds processes to function correctly
Byzantine Fault Tolerance

- Detecting a faulty process is easier
  - $2k+1$ to detect $k$ faults

- Reaching agreement is harder
  - Need $3k+1$ processes (2/3rd majority needed to eliminate the faulty processes)

- Implications on real systems:
  - How many replicas?
  - Separating agreement from execution provides savings
Reaching Agreement

- If message delivery is unbounded,
  - No agreement can be reached even if one process fails
  - Slow process indistinguishable from a faulty one

- BAR Fault Tolerance
  - Until now: nodes are byzantine or collaborative
  - New model: Byzantine, Altruistic and Rational
  - Rational nodes: report timeouts etc
Reliable One-One Communication

- Issues were discussed in Lecture 3
  - Use reliable transport protocols (TCP) or handle at the application layer
- RPC semantics in the presence of failures
- Possibilities
  - Client unable to locate server
  - Lost request messages
  - Server crashes after receiving request
  - Lost reply messages
  - Client crashes after sending request
Reliable One-Many Communication

• Reliable multicast
  – Lost messages => need to retransmit

• Possibilities
  – ACK-based schemes
    • Sender can become bottleneck
  – NACK-based schemes
Atomic Multicast

• Atomic multicast: a guarantee that all process received the message or none at all
  – Replicated database example
  – Need to detect which updates have been missed by a faulty process
• Problem: how to handle process crashes?
• Solution: group view
  – Each message is uniquely associated with a group of processes
    • View of the process group when message was sent
    • All processes in the group should have the same view (and agree on it)

Virtually Synchronous Multicast
Implementing Virtual Synchrony in Isis

(a) Process 4 notices that process 7 has crashed, sends a view change
(b) Process 6 sends out all its unstable messages, followed by a flush message
(c) Process 6 installs the new view when it has received a flush message from everyone else
## Implementing Virtual Synchrony

<table>
<thead>
<tr>
<th>Multicast</th>
<th>Basic Message Ordering</th>
<th>Total-Ordered Delivery?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliable multicast</td>
<td>None</td>
<td>No</td>
</tr>
<tr>
<td>FIFO multicast</td>
<td>FIFO-ordered delivery</td>
<td>No</td>
</tr>
<tr>
<td>Causal multicast</td>
<td>Causal-ordered delivery</td>
<td>No</td>
</tr>
<tr>
<td>Atomic multicast</td>
<td>None</td>
<td>Yes</td>
</tr>
<tr>
<td>FIFO atomic multicast</td>
<td>FIFO-ordered delivery</td>
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<tr>
<td>Causal atomic multicast</td>
<td>Causal-ordered delivery</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Distributed Commit

• Atomic multicast example of a more general problem
  – All processes in a group perform an operation or not at all
  – Examples:
    • Reliable multicast: Operation = delivery of a message
    • Distributed transaction: Operation = commit transaction

• Problem of distributed commit
  – All or nothing operations in a group of processes

• Possible approaches
  – Two phase commit (2PC) [Gray 1978 ]
  – Three phase commit
Two Phase Commit

- Coordinator process coordinates the operation
- Involves two phases
  - Voting phase: processes vote on whether to commit
  - Decision phase: actually commit or abort
Implementing Two-Phase Commit

actions by coordinator:

while START 2PC to local log;
multicast VOTE_REQUEST to all participants;
while not all votes have been collected {
    wait for any incoming vote;
    if timeout {
        while GLOBAL_ABORT to local log;
multicast GLOBAL_ABORT to all participants;
        exit;
    }
    record vote;
}
if all participants sent VOTE_COMMIT and coordinator votes COMMIT {
    write GLOBAL_COMMIT to local log;
multicast GLOBAL_COMMIT to all participants;
} else {
    write GLOBAL_ABORT to local log;
multicast GLOBAL_ABORT to all participants;
}

• Outline of the steps taken by the coordinator in a two phase commit protocol
Implementing 2PC

actions by participant:

write INIT to local log;
wait for VOTE_REQUEST from coordinator;
if timeout {
    write VOTE_ABORT to local log;
    exit;
}
if participant votes COMMIT {
    write VOTE_COMMIT to local log;
    send VOTE_COMMIT to coordinator;
    wait for DECISION from coordinator;
    if timeout {
        multicast DECISION_REQUEST to other participants;
        wait until DECISION is received; /* remain blocked */
        write DECISION to local log;
    }
    if DECISION == GLOBAL_COMMIT
        write GLOBAL_COMMIT to local log;
    else if DECISION == GLOBAL_ABORT
        write GLOBAL_ABORT to local log;
    } else {
        write VOTE_ABORT to local log;
        send VOTE_ABORT to coordinator;
    }

actions for handling decision requests:

*executed by separate thread */

while true {
    wait until any incoming DECISION_REQUEST is received; /* remain blocked */
    read most recently recorded STATE from the local log;
    if STATE == GLOBAL_COMMIT
        send GLOBAL_COMMIT to requesting participant;
    else if STATE == INIT or STATE == GLOBAL_ABORT
        send GLOBAL_ABORT to requesting participant;
    else
        skip; /* participant remains blocked */
Recovering from a Crash

• If INIT: abort locally and inform coordinator
• If Ready, contact another process Q and examine Q’s state

<table>
<thead>
<tr>
<th>State of Q</th>
<th>Action by P</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMMIT</td>
<td>Make transition to COMMIT</td>
</tr>
<tr>
<td>ABORT</td>
<td>Make transition to ABORT</td>
</tr>
<tr>
<td>INIT</td>
<td>Make transition to ABORT</td>
</tr>
<tr>
<td>READY</td>
<td>Contact another participant</td>
</tr>
</tbody>
</table>
Three-Phase Commit

Two phase commit: problem if coordinator crashes (processes block)
Three phase commit: variant of 2PC that avoids blocking
Replication for Fault Tolerance

• Basic idea: use replicas for the server and data

• Technique 1: split incoming requests among replicas
  – If one replica fails, other replicas take over its load
  – Suitable for crash fault tolerance (each replica produces correct results when it is us).

• Technique 2: send each request to all replicas
  – Replicas vote on their results and take majority result
  – Suitable for BFT (a replica can produce wrong results)
    • 2PC, 3PC, Paxos are techniques
Consensus, Agreement

• Consensus vs Byzantine Agreement vs Agreement
• Achieve reliability in presence of faulty processes
  – requires processes to agree on data value needed for computation
  – Examples: whether to commit a transaction, agree on identity of a leader, atomic broadcasts, distributed locks
• Properties of a consensus protocol with fail-stop failures
  – Agreement: every correct process agrees on same value
  – Termination: every correct process decides some value
  – Validity: If all propose v, all correct processes decides v
  – Integrity: Every correct process decided at most one value and if it decides v, someone must have proposed v.
2PC, 3PC Problems

• Both have problems in presence of failures
  – Safety is ensured but liveness is not

• 2PC
  – must wait for all nodes and coordinator to be up
  – all nodes must vote
  – coordinator must be up

• 3PC
  – handles coordinator failure
  – but network partitions are still an issue

• Paxos: how to reach consensus in distributed systems that can tolerate non-malicious failures?
  – majority rather than all nodes participate
Paxos: fault-tolerant agreement

- Paxos lets nodes agree on same value despite:
  - node failures, network failures and delays
- Use cases:
  - Nodes agree X is primary (or leader)
  - Nodes agree Y is last operation (order operations)
- General approach
  - One (or more) nodes decides to be leader (aka proposer)
  - Leader proposes a value and solicits acceptance from others
  - Leader announces result or tries again
- Proposed independently by Lamport and Liskov
  - Widely used in real systems in major companies
Paxos Requirements

- **Safety (Correctness)**
  - All nodes agree on the same value
  - Agreed value X was proposed by some node

- **Liveness (fault-tolerance)**
  - If less than N/2 nodes fail, remaining nodes will eventually reach agreement
  - Liveness not guaranteed if steady stream of failures

- **Why is agreement hard?**
  - Network partitions
  - Leader crashes during solicitation or after deciding but before announcing results,
  - New leader proposes different value from already decided value,
  - More than one node becomes leader simultaneously....
Paxos Setup

• Entities: Proposer (leader), acceptor, learner
  – Leader proposes value, solicits acceptance from acceptors
  – Acceptors are nodes that want to agree; announce chosen value to learners

• Proposals are ordered by proposal #
  – node can choose any high number to try to get proposal accepted
  – An acceptor can accept multiple proposals
    • If prop with value v chosen, all higher proposals have value v

• Each node maintains
  – n_a, v_a: highest proposal # and accepted value
  – n_h: highest proposal # seen so far
  – my_n: my proposal # in current Paxox
Paxos operation: 3 phase protocol

- **Phase 1 (Prepare phase)**
  - A node decides to be a leader and propose
  - Leader chooses $\text{my}_n > \text{n}_h$
  - Leader sends $\langle\text{prepare, my}_n\rangle$ to all nodes
  - Upon receiving $\langle\text{prepare, n}\rangle$ at acceptor
    - If $n < \text{n}_h$
      - reply $\langle\text{prepare-reject}\rangle$ /* already seen higher # proposal */
    - Else
      - $\text{n}_h = n$ /* will not accept prop lower than n */
      - reply $\langle\text{prepare-ok, n}_a, v_a\rangle$ /* send back previous prop, value/
        /* can be null, if first */
Paxos operation

- **Phase 2 (accept phase)**
  - If leader gets prepare-ok from majority
    - V = non-empty value from highest n_a received
    - If V = null, leader can pick any V
    - Send <accept, my_n, V> to all nodes
  - If leader fails to get majority prepare-ok
    - delay and restart Paxos
  - Upon receiving <accept, n, V>
    - If n < n_h
      - reply with <accept-reject>
    - else
      - n_a=n ; v_a = V; n_h = h; reply <accept-ok>
Paxos Operation

• Phase 3 (decide)
  – If leader gets accept-ok from majority
    • Send <decide, v_a> to all learners
  – If leader fails to get accept-ok from a majority
    • Delay and restart Paxos

• Properties
  – P1: any proposal number is unique
  – P2: any two set of acceptors have at least one node in common
  – P3: value sent in phase 2 is value of highest numbered proposal received in responses in phase 1
Paxos Example

\[\begin{align*}
\text{nh} &= \text{N0:0} \\
\text{na} &= \text{va} = \text{null}
\end{align*}\]

\[\begin{align*}
\text{nh} &= \text{N1:1} \\
\text{na} &= \text{null} \\
\text{va} &= \text{null}
\end{align*}\]

\[\begin{align*}
\text{nh} &= \text{N1:1} \\
\text{na} &= \text{N1:1} \\
\text{va} &= \text{val1}
\end{align*}\]

\[\begin{align*}
\text{nh} &= \text{N2:0} \\
\text{na} &= \text{va} = \text{null}
\end{align*}\]

\[\begin{align*}
\text{nh} &= \text{N1:1} \\
\text{na} &= \text{null} \\
\text{va} &= \text{null}
\end{align*}\]

\[\begin{align*}
\text{nh} &= \text{N1:1} \\
\text{na} &= \text{N1:1} \\
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\text{va} &= \text{val1}
\end{align*}\]
Issues

• Network partitions:
  – With one partition, will have majority on one side and can come to agreement (if nobody fails)

• Timeouts
  – A node has max timeout for each message
  – Upon timeout, declare itself as leader and restart Paxos

• Two leaders
  – Either one leader is not able to decide (does not receive majority accept-oks since nodes see higher proposal from other leader) OR
  – one leader causes the other to use it value

• Leader failures: same as two leaders or timeout occurs
Raft Consensus Protocol

- Paxos is hard to understand (single vs multi-paxos)
- Raft - *understandable* consensus protocol
- **State Machine Replication (SMR)**
  - Implemented as a replicated log
  - Each server stores a log of commands, executes in order
  - Incoming requests —> replicate into logs of servers
  - Each server executed request log in order: stays consistent
- Raft: first elect a leader
- Leader sends requests (log entries) to followers
- If **majority** receive entry: safe to apply -> commit
  - If entry committed, all entries preceding it are committed