Distributed Systems (COMP9243)

Lecture 6: Fault Tolerance

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Failure
Reliable Communication
Process Resilience
Recovery

Case Study: AWS Failure 2011

April 21, 2011
EBS (Elastic Block Store) in US East region unavailable for about 2 days
13% of volumes in one availability zone got stuck
led to control API errors and outage in whole region
led to problems with EC2 instances and RDS in most popular region
due to reconfig error and re-mirroring storm.
http://aws.amazon.com/message/65648/

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AWS EBS Overview:
Region → Availability Zones
Clusters → Nodes → Volumes
Control Plane Services: API for volumes for whole region
Networks: primary, secondary
Volume: replicated in cluster

What happened?:
network config problem
re-mirroring storm
CP API thread starvation
node race condition
CP election overload

Slde 4
**TERMINOLOGY:**

**Failure:** a system fails when it fails to meet its promises or cannot provide its services in the specified manner.

**Error:** part of the system state that leads to failure (i.e., it differs from its intended value).

**Fault:** the cause of an error (results from design errors, manufacturing faults, deterioration, or external disturbance).

**Recursive:**
- Failure can be a fault
- Manufacturing fault leads to disk failure
- Disk failure is a fault that leads to database failure
- Database failure is a fault that leads to email service failure

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**TOTAL VS PARTIAL FAILURE**

**Total Failure:**
- All components in a system fail
- Typical in nondistributed system

**Partial Failure:**
- One or more (but not all) components in a distributed system fail
- Some components affected
- Other components completely unaffected
- Considered as fault for the whole system

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**CATEGORISING FAULTS AND FAILURES**

**Types of Faults:**

- **Transient Fault:** occurs once then disappear
- **Intermittent Fault:** occurs, vanishes, reoccurs, vanishes, etc.
- **Permanent Fault:** persists until faulty component is replaced

**Types of Failures:**

- **Process Failure:** process proceeds incorrectly or not at all
- **Storage Failure:** “stable” secondary storage is inaccessible
- **Communication Failure:** communication link or node failure

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**FAILURE MODELS**

**Crash Failure:** a server halts, but works correctly until it halts
- **Fail-Stop:** server will stop in a way that clients can tell that it has halted.
- **Fail-Resume:** server will stop, then resume execution at a later time.
- **Fail-Silent:** clients do not know server has halted

**Omission Failure:** a server fails to respond to incoming requests
- **Receive Omission:** fails to receive incoming messages
- **Send Omission:** fails to send messages
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**Timing Failure:** a server's response lies outside the specified time interval

**Response Failure:** a server's response is incorrect
- **Value Failure:** the value of the response is wrong
- **State Transition Failure:** the server deviates from the correct flow of control

**Arbitrary Failure:** a server may produce arbitrary response at arbitrary times (aka Byzantine failure)

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**Detecting Failure**

**Failure Detector:**
- Service that detects process failures
- Answers queries about status of a process

**Reliable:**
- **Failed** – crashed
- **Unsuspected** – hint

**Unreliable:**
- **Suspected** – may still be alive
- **Unsuspected** – hint

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**Synchronous systems:**
- Timeout
- Failure detector sends probes to detect crash failures

**Asynchronous systems:**
- Timeout gives no guarantees
- Failure detector can track suspected failures
- Combine results from multiple detectors
- How to distinguish communication failure from process failure?
- Ignore messages from suspected processes
- Turn an asynchronous system into a synchronous one

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**Fault Tolerance**

**Fault Tolerance:**
- System can provide its services even in the presence of faults

**Goal:**
- Automatically recover from partial failure
- Without seriously affecting overall performance

**Techniques:**
- **Prevention:** prevent or reduce occurrence of faults
- **Prediction:** predict the faults that can occur and deal with them
- **Masking:** hide the occurrence of the fault
- **Recovery:** restore an erroneous state to an error-free state
### Failure Prevention

Make sure faults don’t happen:
- Quality hardware
- Hardened hardware
- Quality software

### Failure Prediction

Deal with expected faults:
- Test for error conditions
- Error handling code
- Error correcting codes
  - checksums
  - erasure codes

### Failure Masking

Try to hide occurrence of failures from other processes

**Mask:**
1. Communication Failure → Reliable Communication
2. Process Failure → Process Resilience

### Redundancy:

- Information redundancy
- Time redundancy
- Physical redundancy
**RELIABLE COMMUNICATION**

- Communication channel experiences failure
- Focus on masking crash (lost/broken connections) and omission (lost messages) failures

**Two Army Problem:**
Non-faulty processes but lossy communication.

- 1 → 2 attack!
- 2 → 1 ack
- 2: did 1 get my ack?
- 1: 2 ack ack
- 1: did 2 get my ack ack?
- etc.

Consensus with lossy communication is impossible. Why does TCP work?

**RELIABLE POINT-TO-POINT COMMUNICATION**

- Reliable transport protocol (e.g., TCP)
  - Masks omission failure
  - Not crash failure

**Example: Failure and RPC:**
Possible failures:
- Client cannot locate server
- Request message to server is lost
- Server crashes after receiving a request
- Reply message from server is lost
- Client crashes after sending a request

How to deal with the various kinds of failure?
RELIABLE GROUP COMMUNICATION

Receiver missed message #24

Last = 24

Receiver missed message #25

Last = 25

Receiver missed message #23

Last = 23

Receiver missed message #24

Last = 24

Feedback Implosion: sender is swamped with feedback messages

Nonhierarchical Multicast:

- Use NACKs
- Feedback suppression: NACKs multicast to everyone
- Prevents other receivers from sending NACKs if they’ve already seen one.
  - Reduces (N)ACK load on server
  - Receivers have to be coordinated so they don’t all multicast NACKs at same time
  - Multicasting feedback also interrupts processes that successfully received message

Hierarchical Multicast:

Protection against process failures

PROCESS RESILIENCE

SCALABILITY OF RELIABLE MULTICAST

Scale of Reliable Multicast

Long-haul connection

Sender

Coordinator

Root

Local-area network

Receiver

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Groups:
- Organise identical processes into groups
  - Process groups are dynamic
  - Processes can be members of multiple groups
  - Mechanisms for managing groups and group membership
- Deal with all processes in a group as a single abstraction

Flat vs Hierarchical Groups:
- Flat group: all decisions made collectively
- Hierarchical group: coordinator makes decisions

Replication
Create groups using replication
Primary-Based:
- Primary-backup
- Hierarchical group
  - If primary crashes others elect a new primary

Replicated-Write:
- Active replication or Quorum
- Flat group
  - Ordering of requests (atomic multicast problem)

Fault Tolerance:
- Can survive faults in $k$ components and still meet its specifications
  - $k + 1$ replicas enough if fail-silent (or fail-stop)
  - $2k + 1$ required if byzantine

State Machine Replication
Each replica executes as a state machine:
- state + input -> output + new state
- All replicas process same input in same order
- Deterministic: All correct replicas produce same output
- Output from incorrect replicas deviates

Input Messages:
- All replicas agree on content of input messages
- All replicas agree on order of input messages
- Consensus (also called Agreement)

What can cause non-determinism?

Atomic Multicast
A message is delivered to either all processes, or none
Requires agreement about group membership

Process Group:
- Group view: view of the group (list of processes) sender had when message sent
- Each message uniquely associated with a group
- All processes in group have the same view
**View Synchrony:**

A message sent by a crashing sender is either delivered to all remaining processes (crashed after sending) or to none (crashed before sending).

![Diagram of view changes and message delivery](image)

- View changes and messages are delivered in total order. *Why?*

**Implementing View Synchrony:**

- **stable message:** a message that has been received by all members of the group it was sent to.
- Implemented using reliable point-to-point communication (TCP)
- Failure during multicast → only some messages delivered

![Diagram of stable messages](image)

**Agreement**

Examples: Election, transaction commit/abort, dividing tasks among workers, mutual exclusion

- Previous algorithms assumed no faults
- What happens when processes can fail?
- What happens when communication can fail?
- What happens when byzantine failures are possible

We want all nonfaulty processes to reach and establish agreement (within a finite number of steps)

**Variants of the Agreement Problem**

**Consensus:**

- Each process proposes a value
- Communicate with each other...
- All processes decide on the same value
- For example, the maximum of all the proposed values

**Interactive Consistency:**

- All processes agree on a decision vector
- For example, the value that each of the processes proposed

**Byzantine Generals:**

- Commander proposes a value
- All other processes agree on the commander’s value
Correctness of agreement:

Termination all processes eventually decide

Agreement all processes decide on the same value

Validity C. the decided value was proposed by one of the processes
IC. the decided value is a vector that reflects each of the processes proposed values
BG. the decided value was proposed by the commander

Consensus in a Synchronous System

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Assume:

➔ Execution in rounds
➔ Timeout to detect lost messages

Byzantine Generals Problem:

Reliable communication but faulty processes.

➔ n generals (processes)
➔ m. are traitors (will send incorrect and contradictory info)
➔ Need to know everyone else’s troop strength g_i
➔ Each process has a vector: (g_1, …, g_n)
➔ (Note: this is actually interactive consistency)

Byzantine Generals Impossibility:

➔ If m faulty processes then 2m + 1 nonfaulty processes required for correct functioning
Byzantine agreement with Signatures:
➜ Digitally sign messages
➜ Cannot lie about what someone else said
➜ Avoids the impossibility result
➜ Can have agreement with 3 processes and 1 faulty

Consensus in an Asynchronous System

Assume:
➜ Arbitrary execution time (no rounds)
➜ Arbitrary message delays (can’t rely on timeout)

Impossibility of Consensus with One Failure

Impossible to guarantee consensus with $\geq 1$ faulty process

Proof Outline:
➜ Fischer, Lynch, Patterson (FLP) 1985
➜ the basic idea is to show circumstances under which the protocol remains forever indecisive

bivalent vs univalent states
1. There is always a bivalent start state
2. Always possible to reach a bivalent state by delaying messages
→ no termination
In practice we can get close enough

Consensus in Practice

Two Phase Commit:
➜ Original assumption: No failure

Failures can be due to:
➜ Failure of communication channels:
  • use timeouts
➜ Server failures:
  • potentially blocking
Two-phase commit with timeouts: Worker:

- On timeout sends GetDecision.

Two-phase commit with timeouts: Coordinator:

- On timeout re-sends CanCommit, On GetDecision repeats decision.

Coordinator failure:
- When coordinator crashes start a new recovery coordinator
- Learn state of protocol from workers (what did they vote, what did they learn from coordinator)
- Finish protocol

Coordinator and Worker failure: Blocking 2PC:
- Recovery coordinator can’t distinguish between
  - All workers vote Commit and failed worker already committed
  - Failed worker voted Abort and rest of workers voted Commit
- So can’t make a decision

Three Phase Commit
1. Vote: as in 2PC
2. Pre-commit: coordinator sends vote result to all workers, workers acknowledge
3. Commit: coordinator tells workers to perform vote action

Why does this work?
**PAXOS**

Goal: a collection of processes chooses a single proposed value in the presence of failure

**Proposer** proposes value to choose (leader)

**Acceptor** accept or reject proposed values

**Learner** any process interested in the result (chosen value) of the consensus

Chosen Value: value accepted by majority of acceptors

Properties:
- Only proposed values can be learned
- At most one value can be learned
- If a value has been proposed then eventually a value will be learned

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**MULTI PAXOS**

- Paxos allows you to agree on one value
- But, typically need to choose multiple values
  - agree on values
  - agree on order of values
- Run multiple instances of Paxos in sequence
- Each instance to choose a single value
- Add instance id to algorithm
- Track completed instances
- On failure, restart or join last completed instance + 1

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**USING PAXOS**

Use Paxos for:
- Total order multicast: order messages
  - one paxos instance per message: result in a message sequence number
- State machine replication: order operations
  - one paxos instance per operation: result in an operation sequence number
- Leader election: choose a leader id
  - single paxos instance, elections starter(s) propose leader id. result in an agreed upon leader.
- View synchrony: order view changes
  - one paxos instance per view change: result in a view change order sequence number

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**EXAMPLE: STATE MACHINE REPLICAATION**

Conceptually

With Paxos

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API:

```java
val run_proposer(iid, proposed_val)
run_acceptor(iid)
val learn(iid)
```

Client:

```java
while (1){
    ...send(leader, nextop);...
}
```

Replica: Proposer:

```java
while (1) {
    receive op {
        chosen = run_proposer(i++, op);
    } while (chosen != op)
}
```

Replica: Acceptor:

```java
while (1) {
    run_acceptor(i);
}
```

Replica: Learner:

```java
while (1) {
    op = learn(i++);
    exec_op(op);
}
```

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**PAXOS ALGORITHM: 3 PHASES**

Assuming no failures

Phase 1: Propose:

1. Propose: send a proposal `<seq, value>` to \( \geq N/2 \) acceptors
2. Promise: acceptors reply.
   - accept (include last accepted value), promised = seq.

Phase 2: Accept:

1. Accept: when \( \geq N/2 \) accept replies, proposer sends value (as received from acceptor or arbitrary):
2. Accepted: acceptors reply
   - accepted. Remember accepted value.

Phase 3: Learn:

1. Propagate value to Learners when \( \geq N/2 \) accepted replies received.
Failures

Failure Model:
channel: lose, reorder, duplicate message
process: crash (fail-stop, fail-resume)

Failure Cases:
1. Acceptor fails
2. Proposer fails
3. Multiple proposers

Paxos Algorithm: 3 Phases

With Failures!
Phase 1: Propose:
1. Propose: send a proposal <seq, value> to \( \geq N/2 \) acceptors
2. Promise: acceptors reply.
   - reject if seq < seq of previously accepted value
   - else accept (include last accepted value), promised = seq.

Phase 2: Accept:
1. Accept: when \( \geq N/2 \) accept replies, proposer sends value (as received from acceptor or arbitrary):
2. Accepted: acceptors reply
   - reject if seq < promised.
   - else accepted. Remember accepted value.

Phase 3: Learn:
1. Propagate value to Learners when \( \geq N/2 \) accepted received.

Acceptors Fail
- As long as a quorum still available
  - Restart: Must remember last accepted value(s)

Proposer Fails
- Elect a new leader
- Continue execution
- New proposer will choose any previously accepted value
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MULTIPLE PROPOSERS

- For example: crashed proposer returns and continues
- 🎁 Duelling proposers
- ✗ No guaranteed termination
- ✔ Heuristics to recognise situation and back off

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Optimisation and More Information

Opportunities for optimisation:

- Reduce rounds
  - Phase 1: reject: return highest accepted seq
  - Phase 2: reject: return promised seq
- Reduce messages
  - Piggyback multiple requests and replies
  - Pre-propose multiple instances (assumes Proposer rarely fails)

More information:

Paxos Made Live - An Engineering Perspective
Experiences implementing Paxos for Google's Chubby lock server. It turns out to be quite complicated.

Failure Recovery

Restoring an erroneous state to an error free state

Issues:

- Reclamation of resources:
  - locks, buffers held on other nodes
- Consistency:
  - Undo partially completed operations prior to restart
- Efficiency:
  - Avoid restarting whole system from start of computation
**Forward vs. Backward Error Recovery**

**Forward Recovery:**
- Correct erroneous state without moving back to a previous state.
- Example: erasure correction - missing packet reconstructed from successfully delivered packets.
- Possible errors must be known in advance.

**Backward Recovery:**
- Correct erroneous state by moving to a previously correct state.
- Example: packet retransmission when packet is lost.
- General purpose technique.
- High overhead.
- Error can reoccur.
- Sometimes impossible to roll back (e.g. ATM has already delivered the money).

**State-Based Recovery - Checkpointing:**
- Take frequent checkpoints during execution.

**Checkpointing:**
- Pessimistic vs Optimistic:
  - Pessimistic: assumes failure, optimised toward recovery.
  - Optimistic: assumes infrequent failure, minimises checkpointing overhead.
- Independent vs Coordinated:
  - Coordinated: processes synchronise to create global checkpoint.
  - Independent: each process takes local checkpoints independently of others.
- Synchronous vs Asynchronous:
  - Synchronous: distributed computation blocked while checkpoint taken.
  - Asynchronous: distributed computation continues while checkpoint taken.

**Checkpointing Overhead:**
- Frequent checkpointing increases overhead.
- Infrequent checkpointing increases recovery cost.

**Decreasing Checkpointing Overhead:**
- **Incremental checkpointing:** Only write changes since last checkpoint.
  - Write-protect whole address space.
  - On write-fault mark page as dirty and unprotect.
  - On checkpoint only write dirty pages.
- **Asynchronous checkpointing:** Use copy-on-write to checkpoint while execution continues.
  - Easy with UNIX fork().
- **Compress checkpoints:** Reduces storage and I/O cost at the expense of CPU time.
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**RECOVERY IN DISTRIBUTED SYSTEMS**

- Failed process may have causally affected other processes
- Upon recovery of failed process, must undo effects on other processes
- Must roll back all affected processes
- All processes must establish recovery points
- Must roll back to a consistent global state

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**Domino Effect:**

- $P_1$ fails $\rightarrow$ roll back: $P_1 \leftarrow R_{13}$
- $P_2$ fails $\rightarrow P_2 \leftarrow R_{22}$
  - Orphan message $m$ is received but not sent $\rightarrow P_1 \leftarrow R_{12}$
- $P_3$ fails $\rightarrow P_3 \leftarrow R_{32} \rightarrow P_2 \leftarrow R_{21} \rightarrow P_1 \leftarrow R_{11}$, $P_3 \leftarrow R_{31}$

Messaging dependencies plus independent checkpointing may force system to roll back to initial state

**Message Loss:**

- Failure of $P_2$ $\rightarrow P_2 \leftarrow R_{21}$
- Message $m$ is now recorded as sent (by $P_1$) but not received (by $P_2$), and $m$ will never be received after rollback
- Message $m$ is lost
- Whether $m$ is lost due to rollback or due to imperfect communication channels is indistinguishable!
- Require protocols resilient to message loss

**Livelock:**

- $P_2 \downarrow P_2 \leftarrow R_{21} \rightarrow P_1 \leftarrow R_{11}$. Note: $n_1$ in transit
- $P_2 \downarrow P_2 \leftarrow R_{21} \rightarrow P_1 \leftarrow R_{11}$, $n_1$ in transit
- $P_2 \downarrow P_2 \leftarrow R_{21} \rightarrow P_1 \leftarrow R_{11}$, $n_2$ in transit
- Pre-rollback message $n_1$ is received after rollback
- Forces another rollback $P_2 \leftarrow R_{21}$, $P_1 \leftarrow R_{11}$, can repeat indefinitely
**CONSISTENT CHECKPOINTING**

**Consistent Cut:**

- **P1**
- **P2**
- **P3**

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Idea: collect local checkpoints in a coordinated way.

- Set of local checkpoints forms a global checkpoint.
- A global checkpoint represents a consistent system state.

- \{R_{11}, R_{21}, R_{31}\} form a strongly consistent checkpoint:
  - No information flow during checkpoint interval

- \{R_{12}, R_{22}, R_{32}\} form a consistent checkpoint:
  - All messages recorded as received must be recorded as sent

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- **Strongly consistent checkpointing** requires quiescent system
  → Potentially long delays during blocking checkpointing
- **Consistent checkpointing** requires dealing with message loss
  - Not a bad idea anyway, as otherwise each lost message would result in a global rollback
  - Note that a consistent checkpoint may not represent an actual past system state

**How to take a consistent checkpoint?**:

- Simple solution: Each process checkpoints immediately after sending a message
  - High overhead
- Reducing this to checkpointing after \( n \) messages, \( n > 1 \), is **not** guaranteed to produce a consistent checkpoint!
- Require some coordination during checkpointing

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**SYNCHRONOUS CHECKPOINTING**

Processes coordinate local checkpointing so that most recent local checkpoints constitute a consistent checkpoint.

**Assumptions:**

- Communication is via FIFO channels.
- Message loss dealt with via
  - Protocols (such as sliding window), or
  - Logging of all sent messages to stable storage
- Network will not partition

**Local checkpoints:**

- **permanent**: part of a global checkpoint
- **tentative**: may or may not become permanent
**Synchronous Algorithm**

- Global checkpoint initiated by a single coordinator
- Based on 2PC

**First Phase:**
1. Coordinator $P_i$ takes tentative checkpoint
2. $P_i$ sends $i$ message to all other processes $P_j$ to take tentative checkpoint
3. $P_j$ reply to $P_i$ whether succeeded in taking tentative checkpoint
4. $P_i$ receives $true$ reply from each $P_j$ → decides to make permanent
   - $P_i$ receives at least one $false$ → decides to discard the tentative checkpoints

**Second Phase:**
- Coordinator $P_i$ informs all other processes $P_j$ of decision
- Each process replies $true$, unless already in checkpoint or rollback
- If all replies are $true$, coordinator decides to roll back, otherwise continue

**Redundant Checkpoints**

- Algorithm performs unnecessary checkpoints

- $\{R_{11}, R_{21}, R_{31}\}$ form a (strongly) consistent checkpoint
- Checkpoint $\{R_{12}, R_{22}, R_{32}\}$ initiated by $P_i$ is strongly consistent
- $R_{32}$ is redundant, as $\{R_{12}, R_{22}, R_{31}\}$ is consistent

**Rollback Recovery**

**First Phase:**
1. Coordinator sends "r" messages to all other processes to ask them to roll back
2. Each process replies $true$, unless already in checkpoint or rollback
3. If all replies are $true$, coordinator decides to roll back, otherwise continue

**Second Phase:**
1. Coordinator sends decision to other processes
2. Processes receiving this message perform corresponding action
HOMEWORK

Find a Paxos library and implement a replicated state machine using it.

Hacker's edition:

Implement the Paxos library (e.g., in Erlang).

READING LIST

Optional

Paxos Made Live - An Engineering Perspective
Experiences implementing Paxos for Google's Chubby lock server. It turns out to be quite complicated.