Distributed Systems
Principles and Paradigms

Chapter 07

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Introduction

- Basic concepts
- Process resilience
- Reliable client-server communication
- Reliable group communication
- Distributed commit
- Recovery

Dependability

Basics: A *component* provides *services* to *clients*. To provide services, the component may require the services from other components $\Rightarrow$ a component may **depend** on some other component.

Specifically: A component C depends on C^* if the *correctness* of C's behavior depends on the correctness of C^*'s behavior.

Some properties of dependability:

Availability	Readiness for usage
Reliability	Continuity of service delivery
Safety	Very low probability of catastrophes
Maintainability	How easy can a failed system be repaired

Note: For distributed systems, components can be either processes or channels

Terminology

Failure: When a component is not living up to its specifications, a failure occurs

Error: That part of a component's state that can lead to a failure

Fault: The cause of an error

Fault prevention: prevent the occurrence of a fault

Fault tolerance: build a component in such a way that it can meet its specifications in the presence of faults (i.e., **mask** the presence of faults)

Fault removal: reduce the presence, number, seriousness of faults

Fault forecasting: estimate the present number, future incidence, and the consequences of faults

Failure Models

Crash failures: A component simply halts, but behaves correctly before halting

Omission failures: A component fails to respond

Timing failures: The output of a component is correct, but lies outside a specified real-time interval (**performance failures:** too slow)

Response failures: The output of a component is incorrect (but can at least not be accounted to another component)

Value failure: The wrong value is produced
State transition failure: Execution of the component's service brings it into a wrong state

Arbitrary failures: A component may produce arbitrary output and be subject to arbitrary timing failures

Observation: Crash failures are the least severe; arbitrary failures are the worst

Crash Failures

Problem: Clients cannot distinguish between a crashed component and one that is just a bit slow

Examples: Consider a server from which a client is exepcting output:

- Is the server perhaps exhibiting timing or omission failures
- Is the channel between client and server faulty (crashed, or exhibiting timing or omission failures)

Fail-silent: The component exhibits omission or crash failures; clients cannot tell what went wrong

Fail-stop: The component exhibits crash failures, but its failure can be detected (either through announcement or timeouts)

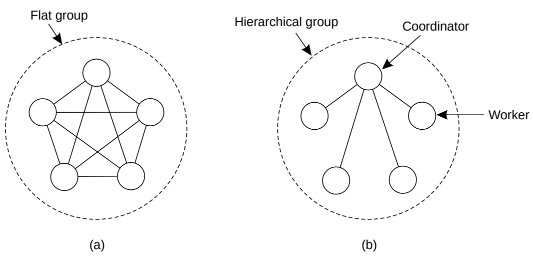
Fail-safe: The component exhibits arbitrary, but benign failures (they can't do any harm)

Process Resilience

Basic issue: Protect yourself against faulty processes by replicating and distributing computations in a group.

Flat groups: Good for fault tolerance as information exchange immediately occurs with all group members; however, may impose more overhead as control is completely distributed (hard to implement).

Hierarchical groups: All communication through a single coordinator ⇒ not really fault tolerant and scalable, but relatively easy to implement.



Groups and Failure Masking (1/3)

Terminology: when a group can mask any k concurrent member failures, it is said to be **k-fault tolerant** (k is called degree of fault tolerance).

Problem: how large does a k-fault tolerant group need to be?

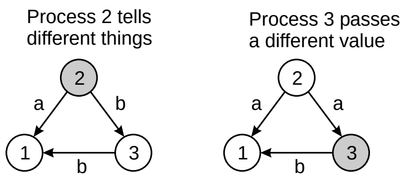
- Assume crash/performance failure semantics ⇒ a total of $k+1$ members are needed to survive k member failures.
- Assume arbitrary failure semantics, and group output defined by voting ⇒ a total of $2k+1$ members are needed to survive k member failures.

Assumption: all members are identical, and process all input in the same order ⇒ only then are we sure that they do exactly the same thing.

Groups and Failure Masking (2/3)

Assumption: Group members are not identical, i.e., we have a distributed computation

Problem: Nonfaulty group members should reach agreement on the same value



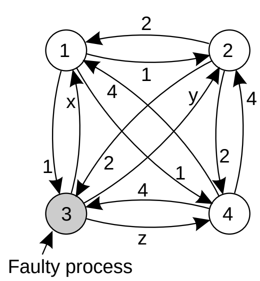
(a) (b)

Observation: Assuming arbitrary failure semantics, we need $3k+1$ group members to survive the attacks of k faulty members

Note: This is also known as **Byzantine failures**.

Essence: We are trying to reach a majority vote among the group of loyalists, in the presence of k traitors $\Rightarrow$ need $2k+1$ loyalists.

Groups and Failure Masking (3/3)



(a)

1	Got(1, 2, x, 4)
2	Got(1, 2, y, 4)
3	Got(1, 2, 3, 4)
4	Got(1, 2, z, 4)

(b)

1 Got	2 Got	4 Got
(1, 2, y, 4)	(1, 2, x, 4)	(1, 2, x, 4)
(a, b, c, d)	(e, f, g, h)	(1, 2, y, 4)
(1, 2, z, 4)	(1, 2, z, 4)	(i, j, k, l)

(c)

(a) what they send to each other
(b) what each one got from the other
(c) what each one got in second step

Reliable Communication

So far: Concentrated on **process resilience** (by means of process groups). What about reliable communication channels?

Error detection:

- Framing of packets to allow for bit error detection
- Use of frame numbering to detect packet loss

Error correction:

- Add so much redundancy that corrupted packets can be automatically *corrected*
- Request retransmission of lost, or last N packets

Observation: Most of this work assumes point-to-point communication

Reliable RPC (1/3)

What can go wrong?:

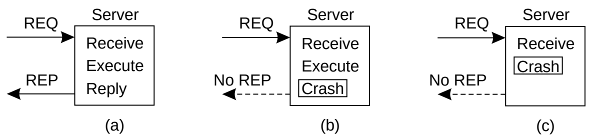
1: Client cannot locate server
2: Client request is lost
3: Server crashes
4: Server response is lost
5: Client crashes

[1:] Relatively simple – just report back to client

[2:] Just resend message

Reliable RPC (2/3)

[3:] Server crashes are harder as you don't what it had already done:



Problem: We need to decide on what we expect from the server

- **At-least-once-semantics:** The server guarantees it will carry out an operation at least once, no matter what
- **At-most-once-semantics:** The server guarantees it will carry out an operation at most once.

Reliable RPC (3/3)

[4:] Detecting lost replies can be hard, because it can also be that the server had crashed. You don't know whether the server has carried out the operation

Solution: None, except that you can try to make your operations **idempotent**: repeatable without any harm done if it happened to be carried out before.

[5:] **Problem:** The server is doing work and holding resources for nothing (called doing an **orphan** computation).

- Orphan is killed (or rolled back) by client when it reboots
- Broadcast new epoch number when recovering $\Rightarrow$ servers kill orphans
- Require computations to complete in a T time units. Old ones are simply removed.

Question: What's the rolling back for?

Reliable Multicasting (1/2)

Basic model: We have a **multicast channel** c with two (possibly overlapping) groups:

- **The sender group** *SND*(c) of processes that *submit* messages to channel c
- **The receiver group** *RCV*(c) of processes that can receive messages from channel c

Simple reliability: If process $P \in RCV(c)$ at the time message m was submitted to c, and P does not leave $RCV(c)$, m should be delivered to P

Atomic multicast: How can we ensure that a message m submitted to channel c is delivered to process $P \in RCV(c)$ only if m is delivered to *all* members of $RCV(c)$

Reliable Multicasting (2/2)

Observation: If we can stick to a local-area network, reliable multicasting is "easy"

Principle: Let the sender log messages submitted to channel c:

- If P sends message m, m is stored in a **history buffer**
- Each receiver acknowledges the receipt of m, or requests retransmission at P when noticing message lost
- Sender P removes m from history buffer when everyone has acknowledged receipt

Question: Why doesn't this scale?

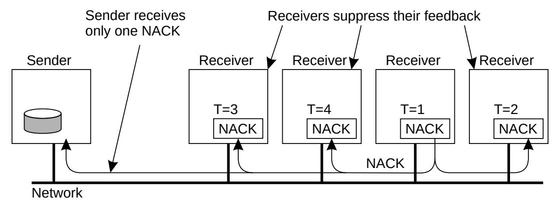
Scalable Reliable Multicasting: Feedback Suppression

Basic idea: Let a process P suppress its own feedback when it notices another process Q is already asking for a retransmission

Assumptions:

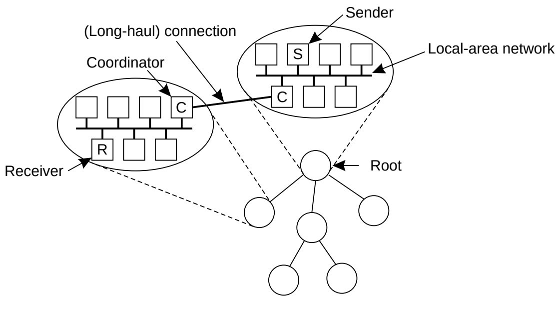
- All receivers listen to a common **feedback channel** to which feedback messages are submitted
- Process P schedules its own feedback message *randomly*, and suppresses it when observing another feedback message

Question: Why is the random schedule so important?



Scalable Reliable Multicasting: Hierarchical Solutions

Basic solution: Construct an hierarchical feedback channel in which all submitted messages are sent only to the root. Intermediate nodes aggregate feedback messages before passing them on.

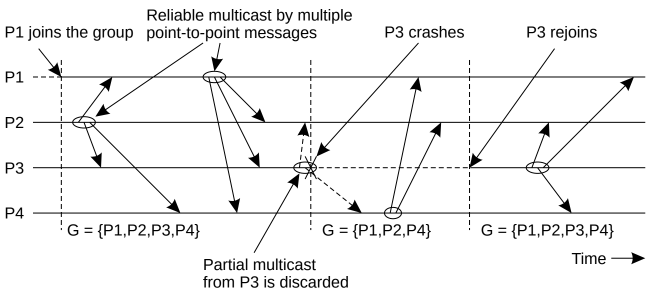


Question: What's the main problem with this solution?

Observation: Intermediate nodes can easily be used for retransmission purposes

Atomic Multicast

Idea: Formulate reliable multicasting in the presence of process failures in terms of process groups and changes to group membership:



Guarantee: A message is delivered only to the non-faulty members of the current group. All members should agree on the current group membership.

Keyword: Virually synchronous multicast

Virtual Synchrony (1/2)

Essence: We consider **views** $V \subseteq RCV(c) \cup SND(c)$

Processes are added or deleted from a view V through **view changes** to V^*; a view change is to be executed *locally* by each $P \in V \cap V^*$

(1) For each consistent state, there is a **unique view** on which all its members agree. **Note:** implies that all nonfaulty processes see all view changes in the same order

(2) If message m is sent to V before a view change vc to V^*, then either all $P \in V$ that excute vc receive m, or no processes $P \in V$ that execute vc receive m. **Note:** all nonfaulty members in the same view get to see the same set of multicast messages.

(3) A message sent to view V can be delivered only to processes in V, and is discarded by successive views

A reliable multicast algorithm satisfying (1)–(3) is **virtually synchronous**

Virtual Synchrony (2/2)

- A sender to a view V need not be member of V
- If a sender $S \in V$ crashes, its multicast message m is *flushed* before S is removed from V: m will never be delivered after the point that $S \notin V$

  Note: Messages from S may still be delivered to all, or none (nonfaulty) processes in V before they all agree on a new view to which S does not belong
- If a receiver P fails, a message m may be lost but can be recovered as we know exactly what has been received in V. Alternatively, we may decide to deliver m to members in $V - \{P\}$

Observation: Virtually synchronous behavior can be seen independent from the ordering of message delivery. The only issue is that messages are delivered to an *agreed upon* group of receivers.

Virtual Synchrony Implementation (1/3)

- The current view is known at each P by means of a delivery list dest[P]
- If $P \in$ dest[Q] then $Q \in$ dest[P]
- Messages received by P are queued in queue[P]
- If P fails, the group view must change, but not before all messages from P have been flushed
- Each P attaches a (stepwise increasing) **timestamp** with each message it sends
- Assume FIFO-ordered delivery; the highest numbered message from Q that has been received by P is recorded in rcvd[P][Q]
- The vector rcvd[P][] is sent (as a control message) to all members in dest[P]
- Each P records rcvd[Q][] in remote[P][Q]

Virtual Synchrony Implementation (2/3)

Observation: remote[P][Q] shows what P knows about message arrival at Q

1	2	3	1	5
2	2	2	2	4
3	3	1	4	5
4	4	2	2	4
min	2	1	1	4

A message is **stable** if it has been received by all $Q \in$ dest[P] (shown as the **min** vector)

Stable messages can be delivered to the next layer (which may deal with ordering). **Note:** Causal message delivery comes for free

As soon as all messages from the faulty process have been flushed, that process can be removed from the (local) views

Virtual Synchrony Implementation (3/3)

Remains: What if a sender P failed and not all its messages made it to the nonfaulty members of the current view?

Solution: Select a coordinator which has all (unstable) messages from P, and forward those to the other group members.

Note: Member failure is assumed to be detected and subsequently multicast to the current view as a view change. That view change will not be carried out before all messages in the current view have been delivered.

Distributed Commit

- Two-phase commit
- Three-phase commit

Essential issue: Given a computation distributed across a process group, how can we ensure that either all processes commit to the final result, or none of them do (**atomicity**)?

Two-Phase Commit (1/2)

Model: The client who inititated the computation acts as coordinator; processes required to commit are the participants

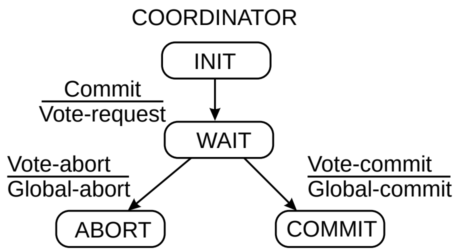
Phase 1a: Coordinator sends VOTE_REQUEST to participants (also called a **pre-write**)

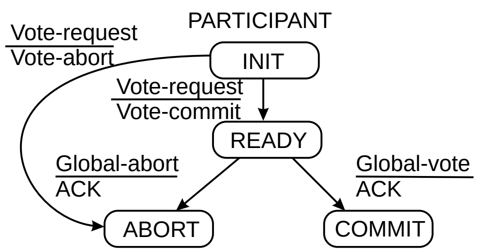
Phase 1b: When participant receives VOTE_REQUEST it returns either YES or NO to coordinator. If it sends NO, it aborts its local computation

Phase 2a: Coordinator collects all votes; if all are YES, it sends COMMIT to all participants, otherwise it sends ABORT

Phase 2b: Each participant waits for COMMIT or ABORT and handles accordingly.

Two-Phase Commit (2/2)





2PC – Failing Participant

Observation: Consider participant crash in one of its states, and the subsequent recovery to that state:

Initial state: No problem, as participant was unaware of the protocol

Ready state: Participant is waiting to either commit or abort. After recovery, participant needs to know which state transition it should make ⇒ log the coordinator's decision

Abort state: Merely make entry into abort state *idem-potent*, e.g., removing the workspace of results

Commit state: Also make entry into commit state idem-potent, e.g., copying workspace to storage.

Observation: When distributed commit is required, having participants use temporary workspaces to keep their results allows for simple recovery in the presence of failures.

2PC – Failing Coordinator

Observation: The real problem lies in the fact that the coordinator's final decision may not be available for some time (or actually lost)

Alternative: Let a participant P in the ready state timeout when it hasn't received the coordinator's decision; P tries to find out what other participants know.

Question: Can P *not* succeed in getting the required information?

Observation: Essence of the problem is that a recovering participant cannot make a **local** decision: it is dependent on other (possibly failed) processes

Three-Phase Commit (1/2)

Phase 1a: Coordinator sends VOTE_REQUEST to participants

Phase 1b: When participant receives VOTE_REQUEST it returns either YES or NO to coordinator. If it sends NO, it aborts its local computation

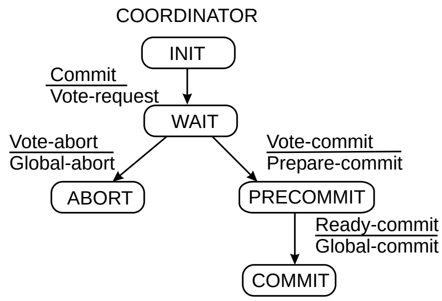
Phase 2a: Coordinator collects all votes; if all are YES, it sends PREPARE to all participants, otherwise it sends ABORT, and halts

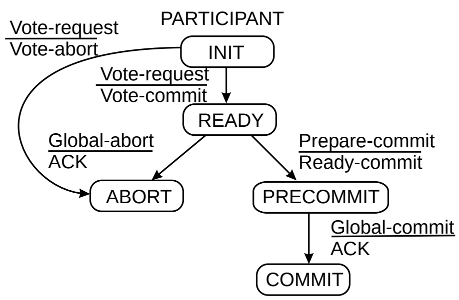
Phase 2b: Each participant waits for PREPARE, or waits for ABORT after which it halts

Phase 3a: (Prepare to commit) Coordinator waits until all participants have ACKed receipt of PREPARE message, and then sends COMMIT to all

Phase 3b: (Prepare to commit) Participant waits for COMMIT

Three-Phase Commit (2/2)





3PC – Failing Participant

Basic issue: Can P find out what it should it do after crashing in the ready or pre-commit state, even if other participants or the coordinator failed?

Essence: Coordinator and participants on their way to commit, never differ by more than one state transition

Consequence: If a participant timeouts in ready state, it can find out at the coordinator or other participants whether it should abort, or enter pre-commit state

Observation: If a participant already made it to the pre-commit state, it can always safely commit (but is not allowed to do so for the sake of failing other processes)

Observation: We may need to elect another coordinator to send off the final COMMIT

Recovery

- Introduction
- Checkpointing
- Message Logging

Recovery: Background

Essence: When a failure occurs, we need to bring the system into an error-free state:

- **Forward error recovery:** Find a new state from which the system can continue operation
- **Backward error recovery:** Bring the system back into a *previous* error-free state

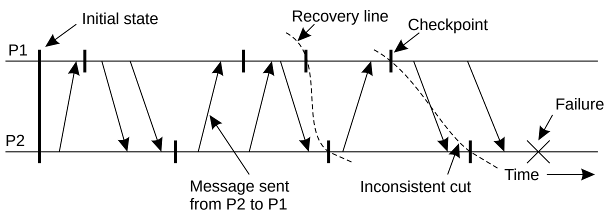
Practice: Use backward error recovery, requiring that we establish **recovery points**

Observation: Recovery in distributed systems is complicated by the fact that processes need to cooperate in identifying a **consistent state** from where to recover

Consistent Recovery State

Requirement: Every message that has been received is also shown to have been sent in the state of the sender

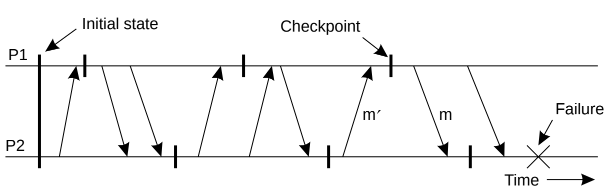
Recovery line: Assuming processes regularly **checkpoint** their state, the most recent **consistent global checkpoint**.



Observation: If and only if the system provides *reliable* communication, should sent messages also be received in a consistent state

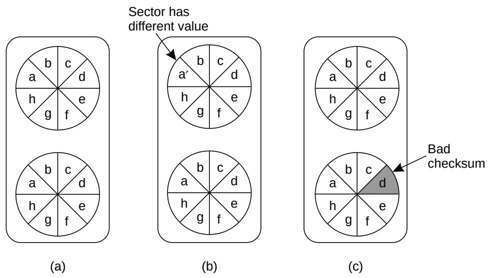
Cascaded Rollback

Observation: If checkpointing is done at the "wrong" instants, the recovery line may lie at system startup time ⇒ **cascaded rollback**



Checkpointing: Stable Storage

Principle: Replicate all data on at least two disks, and keep one copy "correct" at all times.



After a crash:

- If both disks are identical: you're in good shape.
- If one is bad, but the other is okay (checksums): choose the good one.
- If both seem okay, but are different: choose the main disk.
- If both aren't good: you're **not** in a good shape.

Independent Checkpointing

Essence: Each process independently takes checkpoints, with the risk that a cascaded rollback to system startup.

- Let $CP[i](m)$ denote m^{th} checkpoint of process P_i and $INT[i](m)$ the interval between $CP[i](m-1)$ and $CP[i](m)$
- When process P_i sends a message in interval $INT[i](m)$, it piggybacks (i, m)
- When process P_j receives a message in interval $INT[j](n)$, it records the dependency $INT[i](m) \rightarrow INT[j](n)$
- The dependency $INT[i](m) \rightarrow INT[j](n)$ is saved to stable storage when taking checkpoint $CP[j](n)$

Observation: If process P_i rolls back to $CP[i](m-1)$, P_j must roll back to $CP[j](n-1)$. **Question:** How can P_j find out where to roll back to?

Coordinated Checkpointing

Essence: Each process takes a checkpoint after a globally coordinated action

Question: What advantages are there to coordinated checkpointing?

Simple solution: Use a two-phase blocking protocol:

- A coordinator multicasts a *checkpoint request* message
- When a participant receives such a message, it takes a checkpoint, stops sending (application) messages, and reports back that it has taken a checkpoint
- When all checkpoints have been confirmed at the coordinator, the latter broadcasts a *checkpoint done* message to allow all processes to continue

Observation: It is possible to consider only those processes that depend on the recovery of the coordinator, and ignore the rest

Message Logging

Alternative: Instead of taking an (expensive) checkpoint, try to **replay** your (communication) behavior from the most recent checkpoint $\Rightarrow$ store messages in a log

Assumption: We assume a **piecewise deterministic** execution model:

- The execution of each process can be considered as a sequence of state intervals
- Each state interval starts with a nondeterministic event (e.g., message receipt)
- Execution in a state interval is deterministic

Conclusion: If we record nondeterministic events (to replay them later), we obtain a deterministic execution model that will allow us to do a complete replay

Question: Why is logging only *messages* not enough?

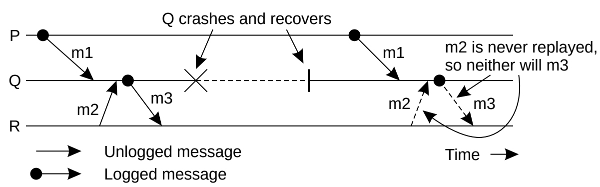
Question: Is logging only nondeterministic events enough?

Message Logging and Consistency

Problem: When should we actually log messages?

Issue: Avoid **orphans**:

- Process Q has just received and subsequently delivered messages m_1 and m_2
- Assume that m_2 is never logged.
- After delivering m_1 and m_2, Q sends message m_3 to process R
- Process R receives and subsequently delivers m_3



Goal: Devise message logging schemes in which orphans do not occur

Message-Logging Schemes (1/2)

HDR[m]: The header of message m containing its source, destination, sequence number, and delivery number

The header contains all information for resending a message and delivering it in the correct order (assume data is reproduced by the application)

A message m is **stable** if HDR[m] cannot be lost (e.g., because it has been written to stable storage)

DEP[m]: The set of processes to which message m has been delivered, as well as any message that causally depends on delivery of m

COPY[m]: The set of processes that have a copy of HDR[m] in their volatile memory

If C is a collection of crashed processes, then $Q \notin C$ is an orphan if there is a message m such that $Q \in \text{DEP}[m]$ and $\text{COPY}[m] \subseteq C$

Message-Logging Schemes (2/2)

Goal: No orphans means that for each message m, $\mathsf{DEP[m]} \subseteq \mathsf{COPY[m]}$

Pessimistic protocol: for each *nonstable* message m, there is at most one process dependent on m, that is $|\mathsf{DEP[m]}| \leq 1$

Consequence: An unstable message in a pessimistic protocol *must* be made stable before sending a next message

Optimistic protocol: for each unstable message m, we ensure that if $\mathsf{COPY[m]} \subseteq C$, then eventually also $\mathsf{DEP[m]} \subseteq C$, where C denotes a set of processes that have been marked as faulty

Consequence: To guarantee that $\mathsf{DEP[m]} \subseteq C$, we generally rollback each orphan process Q until $Q \notin \mathsf{DEP[m]}$