Fault Tolerance

Today

- Introduction to fault tolerance
- Process resilience
- Communication resilience
- Distributed commit
- Recovery

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Dependability

- To understand fault tolerance, we need to understand dependability
- Components provide services, maybe by requiring services from other components ⇒ a component may *depend* on another component
- Some properties of dependability
  - Availability – readiness for usage (probability of operating correctly at any moment)
  - Reliability – continuity of service delivery (rather than probability, uptime)
  - Safety – very low probability of catastrophes
  - Maintainability – how easy can a failed system be repaired
- For distributed systems, components can be either processes or channels

Terminology

- Failure – component cannot meet its promises
- Error – part of a component's state that can lead to a failure
- Fault – the cause of an error
- Fault tolerance – build a component so 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

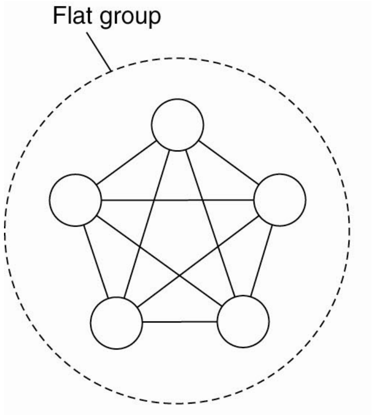
- Crash failures – a component simply halts, but behaves correctly before halting
- Omission failures – … fails to respond to incoming requests
  - Receive or send omission
- Timing failures – output is correct, but lies outside a specified real-time interval
- Response failures – output is incorrect
  - Value failure: The wrong value is produced
  - State transition failure: Execution of the component's service brings it into a wrong state
- Arbitrary/byzantine failures – may produce arbitrary output and be subject to arbitrary timing failures

Crash failures

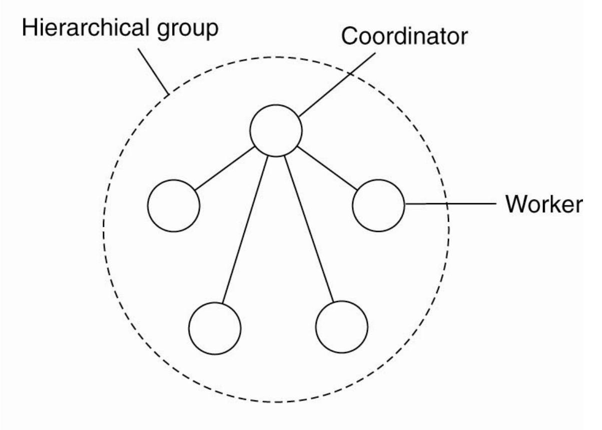
- Clients cannot distinguish between a crashed and a slow component
- Fail-stop – the component exhibits crash failures, but its failure can be detected (either through announcement or timeouts)
- Fail-silent – the component exhibits omission or crash failures; hard to tell what went wrong
- Fail-safe – the component exhibits arbitrary, but benign failures (generating random output)

Process resilience

- Basic approach to masking faults – redundancy
- To protect yourself against faulty processes – replicate and distribute computations in a group.
  - Flat groups
    - Symmetrical, no singe point of failure; decision making is more complicated

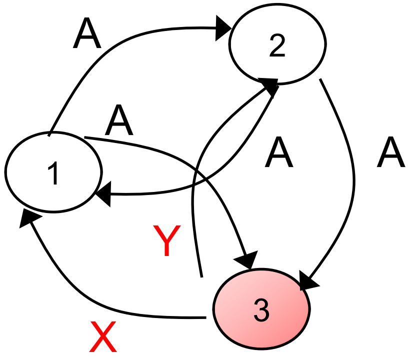


  - Hierarchical groups
    - All communication through a single coordinator ⇒ not really fault tolerant and scalable, but relatively easy to implement.



Groups and failure masking

- A group that can mask *k* concurrent member failures, is k-fault tolerant (*k* is called *degree of fault tolerance)*
- How large does a *k-fault tolerant group* need to be?
  - Assume crash/performance failure semantics ⇒ *2k + 1* members are needed to survive *k* member failures



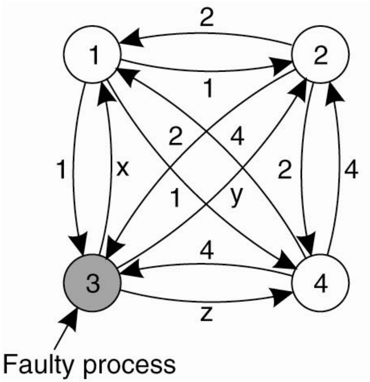
Letter: A

What letter is it?

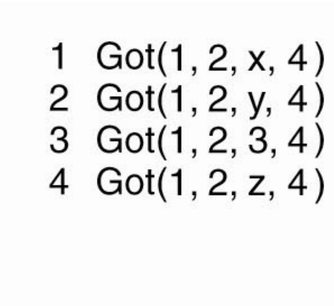
  - Assume arbitrary/Byzantine failure semantics, and group output defined by voting ⇒ *3k+1*
    - Assume processes are synchronous, messages are unicast and preserve ordering, communication delay is bounded
    - Non-faulty group members should reach agreement on the same value

Groups and failure masking

- Each process *i* provides a value v_i to the other *N-1*
- Each process constructs vector *V* of length *N*, such that if process *i* is not faulty, *V[i] = i*, otherwise is undef
- The algorithm operates in four steps
  1. Every non-faulty process i sends v_i to every other using reliable unicast (a)
  2. Results are collected into a vector (b)
  3. Processes exchange their vectors (c)
  4. Result vector is computed with majority value or *UNKNOWN*

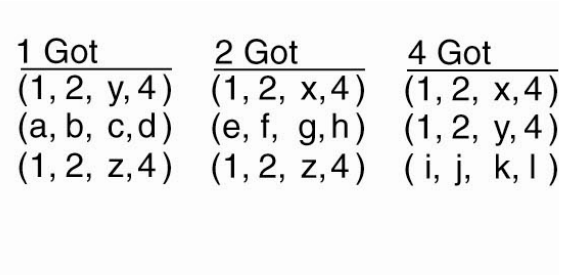


(a)



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)



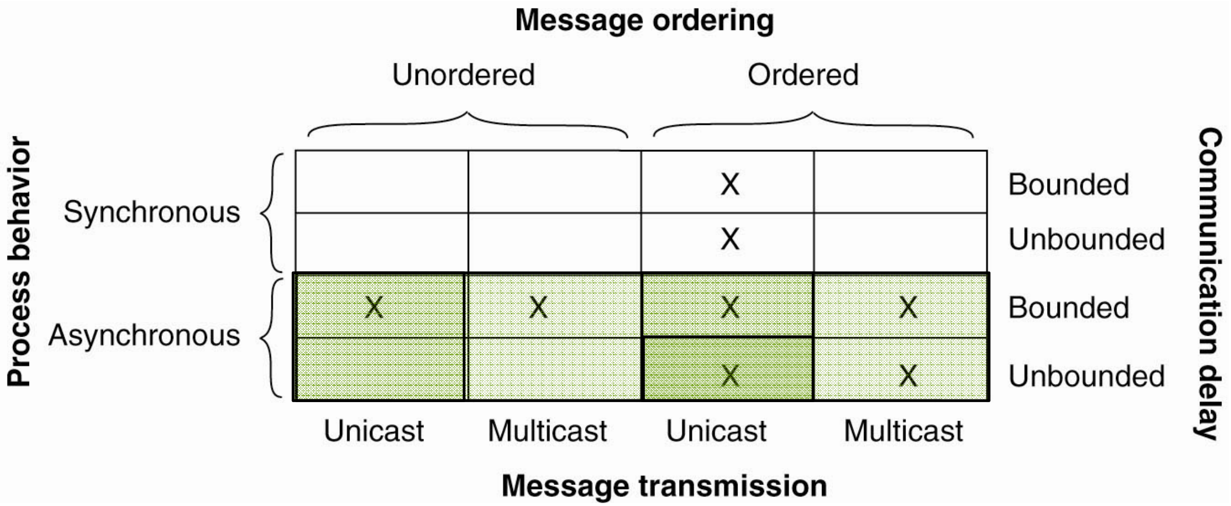
1 Got	2 Got	4 Got
(1, 2, y, 4)	(1, 2, x, 4)	(1, 2, x, 4)
(a, b, c, d)	(e, f, g, h)	(1, 2, y, 4)
(1, 2, z, 4)	(1, 2, z, 4)	(i, j, k, l)

(c)

Groups and failure masking

- What are the necessary conditions for reaching agreement?

In practice, most distributed systems assume …



Message ordering

Process behavior	Communication delay	Unordered		Ordered	
		Unicast	Multicast	Unicast	Multicast
Synchronous	Bounded			X	
	Unbounded			X	
Asynchronous	Bounded	X	X	X	X
	Unbounded			X	X

Message transmission

- Process: Synchronous ⇒ operate in lockstep
- Delays: Are delays on communication bounded?
- Ordering: Are messages delivered in the order they were sent?
- Transmission: Are messages sent one-by-one, or multicast?

Failure detection

- Failure detection is key to fault tolerance
- How do we detect process failures?
  - Keep alive messages
  - Passively wait for a sign
- Basically, detect failures through timeout mechanisms
  - Setting timeouts properly is very difficult and application dependent
  - You cannot distinguish process failures from network failures
  - We need to consider failure notification throughout the system:
    - Gossiping (i.e., proactively disseminate a failure detection)
    - On failure detection, pretend you failed as well

Reliable communication

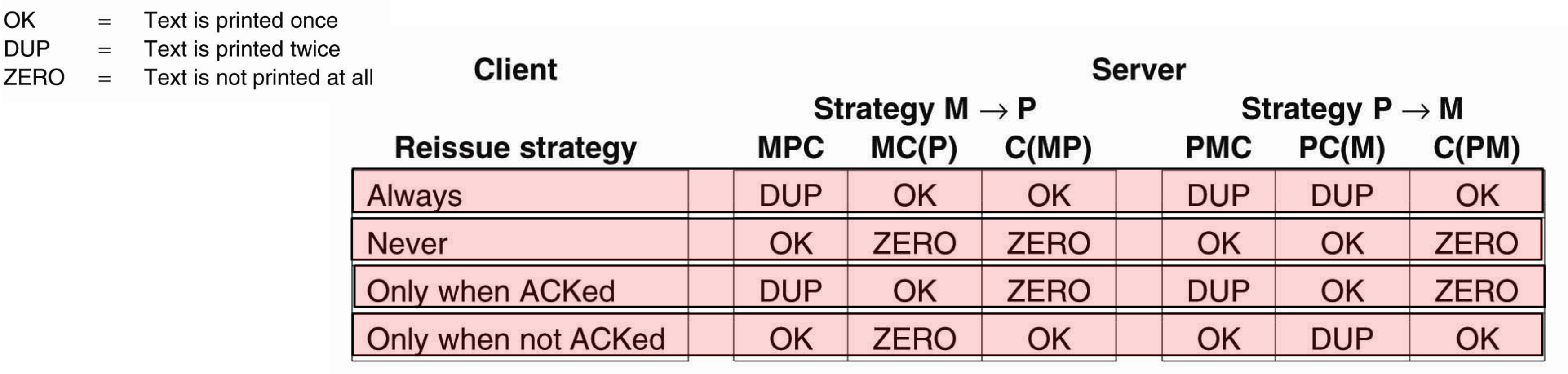
- What about reliable communication channels?
- Error detection:
  - Framing of packets to allow for bit error detection
  - Use of frame numbering to detect packet loss
- Error correction:
  - Add so much redundancy that corrupted packets can be automatically corrected
  - Request retransmission of lost, or last *N packets*
- Most of this work assumes point-to-point communication

Reliable RPC

- What can go wrong with a remote procedure call?
- 1: Client cannot locate server
  - Either went down or has a new version of the interface; relatively simple – just report back to client (of course, that's not *too* transparent)
- 2: Client request is lost
  - Just resend message after a timeout
- 3: Server crashes
  - Harder to handle – we don't know how far it went
  - What should we expect from the server?
    - At-least-once – guarantees an operation at least once, but perhaps more
    - At-most-once – guarantees an operation at most once
    - Exactly-once – *no way to arrange this!*
- …

Reliable RPC

- Exactly-once semantics
  - Client asks to print text, server sends completion
  - Server can
    - Send completion before (M→P) or after printing (P→M)
  - Client can
    - Always reissue, never reissue, reissue request only when ACK, reissue only when not ACK
  - *Not good solution for all situations!*



OK = Text is printed once
DUP = Text is printed twice
ZERO = Text is not printed at all

Client	**Server**					
	Strategy M → P			**Strategy P → M**		
Reissue strategy	**MPC**	**MC(P)**	**C(MP)**	**PMC**	**PC(M)**	**C(PM)**
Always	DUP	OK	OK	DUP	DUP	OK
Never	OK	ZERO	ZERO	OK	OK	ZERO
Only when ACKed	DUP	OK	ZERO	DUP	OK	ZERO
Only when not ACKed	OK	ZERO	OK	OK	DUP	OK

Reliable RPC

- 4: Server response is lost
  - Hard to detect, the server could also had crashed. Did it get it done? Solution: No much, try making operations idempotent
- 5: Client crashes
  - Server is doing work and holding resources for nothing (doing an orphan computation)
    - Orphan is killed (or rolled back) by client when it reboots
    - Broadcast new epoch number when recovering ⇒ servers kill orphans
    - Require computations to complete in a T time units.
  - Old ones are simply removed

Reliable group communication

- Reliable multicast – guarantee that msgs are delivered to all members of a group
- Basic model: A multicast channel *c* with two (possibly overlapping) groups:
  - Sender group *SND(c)* of processes that submit msgs to c
  - Receiver group *RCV(c)* that can receive messages from *c*
- Simple reliability (non-faulty processes) & agreement on *RCV*
  - 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*

Reliable group communication

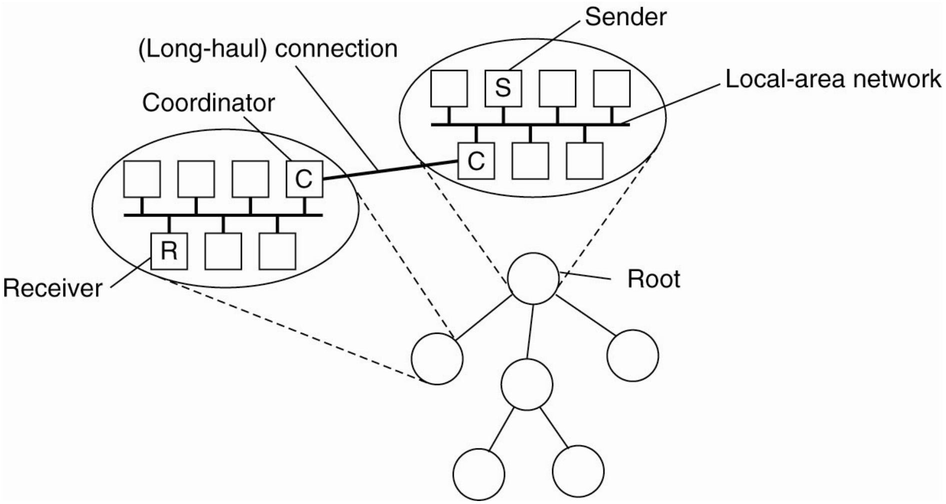
- Observation: If we can stick to a local-area network, reliable multicasting is “easy”
- Let the sender log messages submitted to channel *c:*
  - If *P* sends message *m, m* is stored in a history buffer
  - Each receiver acknowledges the receipt of *m,* or requests retransmission at *P* when noticing message lost
  - Sender *P* removes *m* from history buffer when everyone has acknowledged receipt
- Why doesn’t this scale?
  - N acks!
- Solution – use NACKs instead
  - Issue – how long should you keep the msg in the buffer?

Scalable reliable multicast – SRM

- Let a process *P* suppress its own feedback when it notices another process *Q* is already asking for a retransmission (Floyd et al.'s SRM)
- 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
- A few issues
  - The random interval is key
  - Multicasting feedback also interrupt processes that got the request
  - Other receivers can also help in the recovery

Scalable reliable multicast – hierarchical

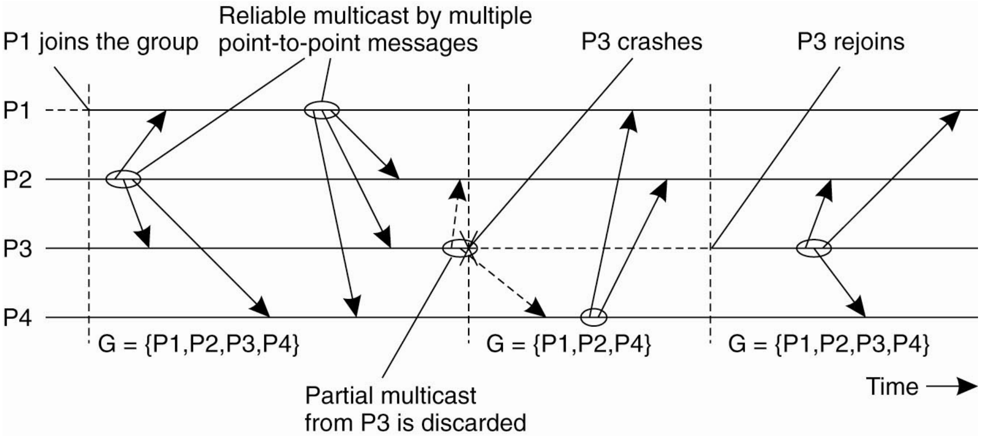
- Add hierarchy for scalability – a hierarchical feedback channel in which all submitted messages are sent only to the root.
- Intermediate nodes aggregate feedback messages before passing them on



- Main problem – tree construction

Atomic multicast

- Atomic multicast – the msg is delivered to all or none
  - A msg is associated with a group of processes, a group view
- Virtual synchronous – a msg is delivered to each non-faulty process in G, if the sender crashes it can either be delivered to all or be ignored by all

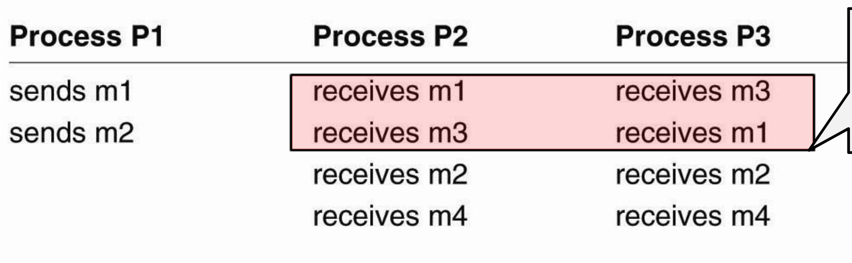


- Virtual synchrony let's us see multicast as happening in epochs separated by group memberships

Message ordering

- What about order of messages?
  - Unordered – virtual synchronous w/o order guarantees
  - FIFO-ordered – from the same process in the same order
  - Causally-ordered – preserving potential causality bet/ different messages
  - Totally-ordered – whether unordered, FIFO or causally ordered, msgs are delivered in same order to all processes
- Virtual synchronous reliable multicasting with totally-ordered delivery – atomic multicasting
  - e.g. causal multicast and causal atomic multicast – causal-ordered without/with total-ordered delivery

Four processes, two senders, one possible FIFO-ordered delivery



Process P1	Process P2	Process P3
sends m1	receives m1	receives m3
sends m2	receives m3	receives m1
	receives m2	receives m2
	receives m4	receives m4

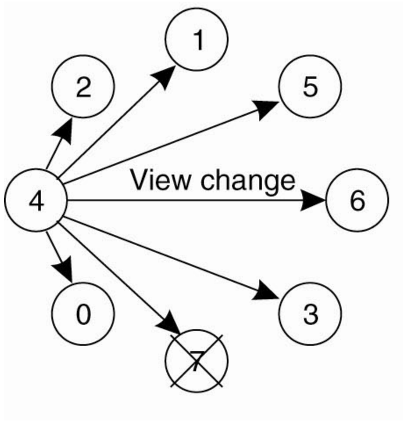
However, this violates total-ordering

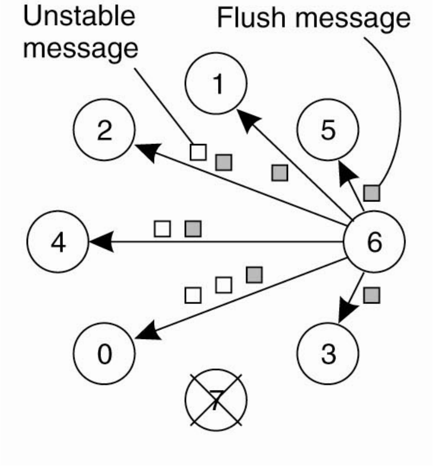
Virtual synchronous multicast in ISIS

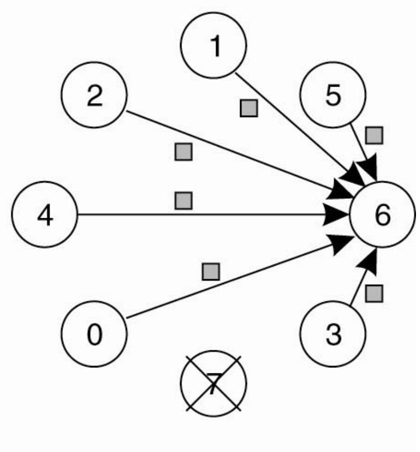
- Relies on reliable, ordered, unicast – TCP
  - Multicast – reliable unicast each member in the group
- Problem to solve – guarantee that all msgs sent to view G are delivery to all non-faulty processes in G before a membership change
- To deal with crashed sender, every process in G keeps the message until it is sure everybody got it – i.e. message is *stable*
- Only stable messages can be delivered

Virtual synchronous multicast in ISIS

- When a process P receives view-change msg for G_{i+1},
  - – Forwards a copy of any unstable message from G_i to all processes in G_{i+1}
    - When Q receives a copy of m sent in Gi, it delivers m (discards it if dup)
  - – Marks message as stable (remember – reliable point-to-point)
  - – To indicate it has no unstable messages left, mcast a flush message
  - – When it receives a flush message from all, installs new view







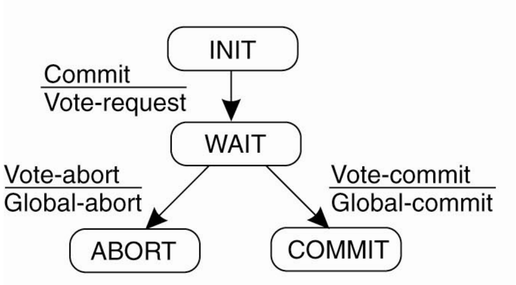
Distributed commit

- Atomic multicast – a form of distributed commit
- Given a computation distributed across a process group, ensure that either all processes commit to the final result, or none of them do
  - One-phase commit
    - Coordinator tells everyone what to do – no way to know if they did it or not
  - Two-phase commit
    - Coordinator makes sure everybody is going to do it
    - It can’t handle coordinator failure
  - Three-phase commit

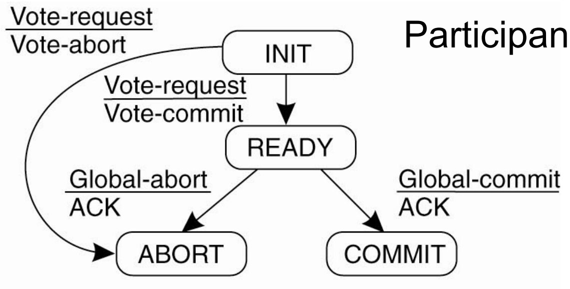
Two-phase commit

- Client that initiates computation acts as coordinator (C); processes required to commit are participants (P)
- Phases
  - 1a: C sends vote-request to all (a pre-write)
  - 1b: When P receives vote-request it returns either vote-commit or vote-abort to C; if it sends vote-abort, it aborts its local computation
  - 2a: C collects all votes; if all are vote-commit, it sends global-commit to all, otherwise it sends global-abort
  - 2b: Each P waits for global-commit or global-abort and handles accordingly

Coordinator



Participant



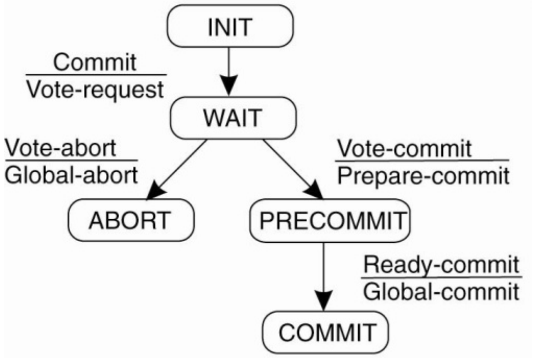
2PC and failures

- Participant
  - Initial state – no problem, P was unaware of the protocol
  - Ready state – waiting to either commit/abort, ask other P what to do
  - Abort state – make intro into abort state idempotent, removing the workspace of results
  - Commit state – also make entry into commit state idempotent, e.g., copying workspace to storage
- Coordinator
  - Record that it is entering WAIT so that it can possible retransmit the VOTE_REQUEST after recovering
  - If it has decided either ABORT or COMMIT, retransmit it when recovered
- If coordinator crashed when all participants have received and process the VOTE_REQUEST, everybody blocks!

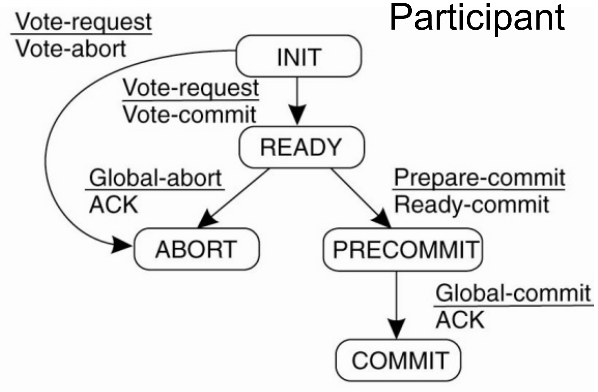
Three-phase commit

- 3PC to avoid blocking processes given fail-stop crash
  - Rarely used, nevertheless, as in practice 2PC works fine
- 3PC
  - 1a: C sends vote-request to all P
  - 1b: P receives vote-request, it returns either vote-commit or vote-abort to C (and aborts its local computation)
  - 2a: C collects all votes; if all vote-commit, sends prepare-commit to all, otherwise sends global-abort and halts
  - 2b: Each P waits for it; if global-abort, halts
  - 3a: C waits until all P have sent ready-commit, sends global-commit to all
  - 3b: P waits for global-commit

Coordinator



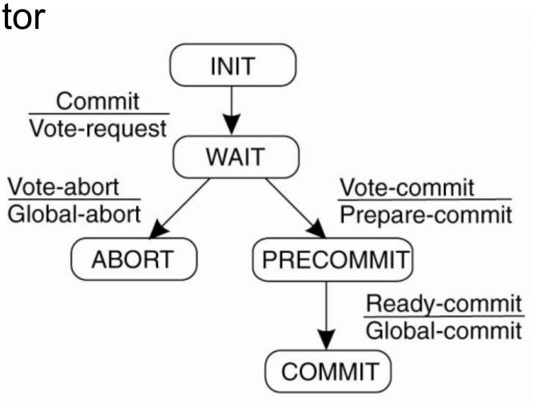
Participant



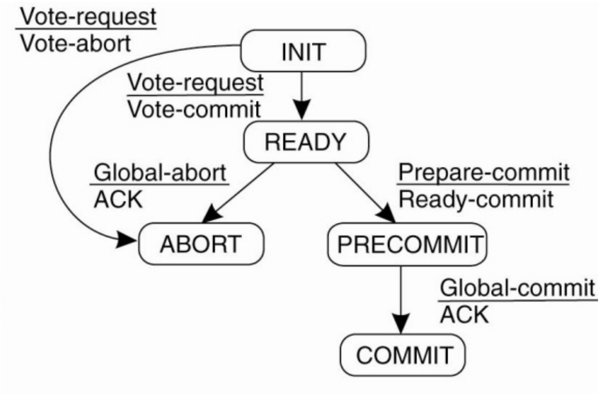
3PC and failures

- If P is waiting in INIT or C in WAIT, ABORT
- C is waiting on PRECOMMIT, GLOBAL_COMMIT
- P is waiting in READY or PRECOMMIT, C failed so ask other P
  - If somebody is in INIT, ABORT. A participant can be in INIT only if nobody is in PRECOMMIT (C needs to get VOTE_COMMIT to move anybody there)
  - If other P is in COMMIT or ABORT, do the same
  - If majority are in PRECOMMIT, commit everybody
  - If majority are in READY, ABORT
- Note, with 3PC a crashed process can only recover to INIT, ABORT or PRECOMMIT (no COMMIT)

Coordinator



Participant

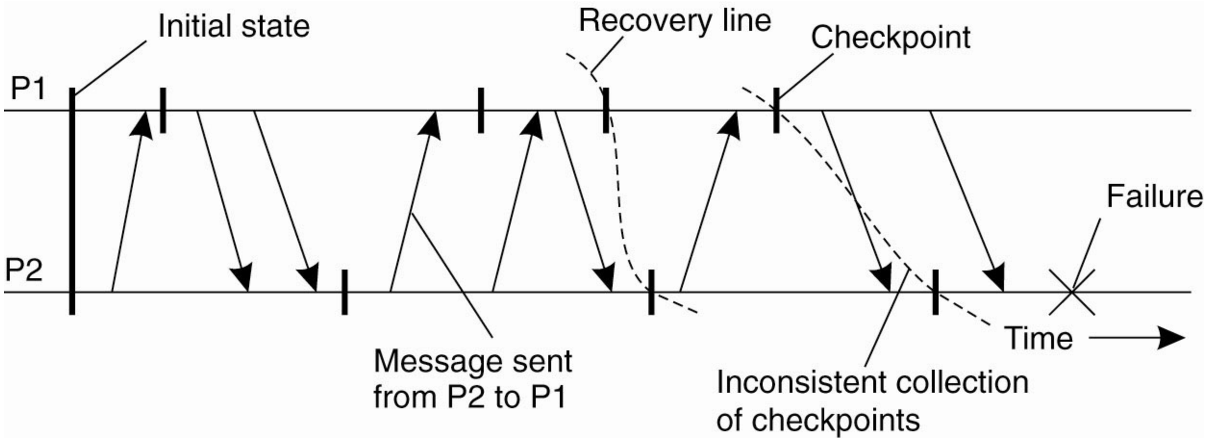


Recovery

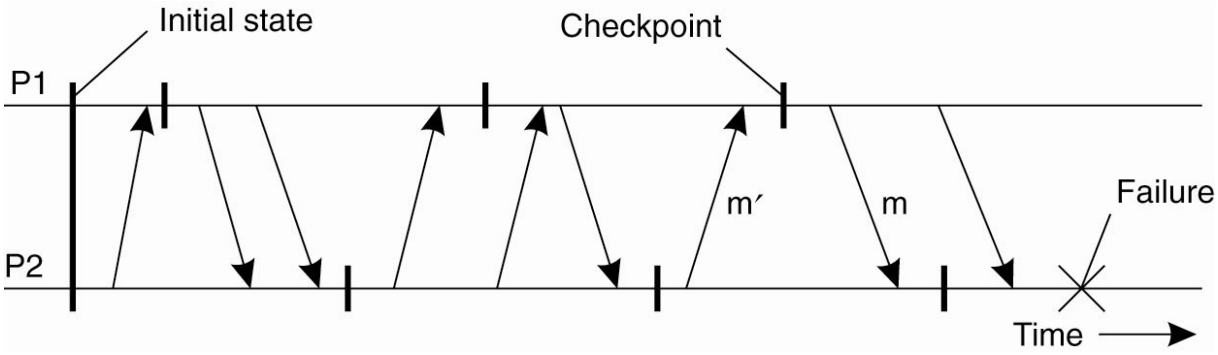
- When a failure occurs, bring system to error-free state
  - Forward error recovery – find a new state from which the system can continue operation, e.g. erasure code
    - Errors must be known in advance
  - Backward error recovery – bring system back into a previous error-free state, e.g. checkpointing & rollback
    - Application independent
    - Use backward error recovery, requires establishing recovery points (kept in stable storage)
    - Not everything can be rollback (ATM withdraw)
    - Performance hit – combine checkpointing with logging
- Recovery in distributed systems – processes need to cooperate in identifying a consistent state from where to recover

Consistent recovery state

- Every message 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



If checkpointing is done at the “wrong” times, the recovery line may lie at system startup time ⇒ cascaded rollback



Coordinated checkpointing

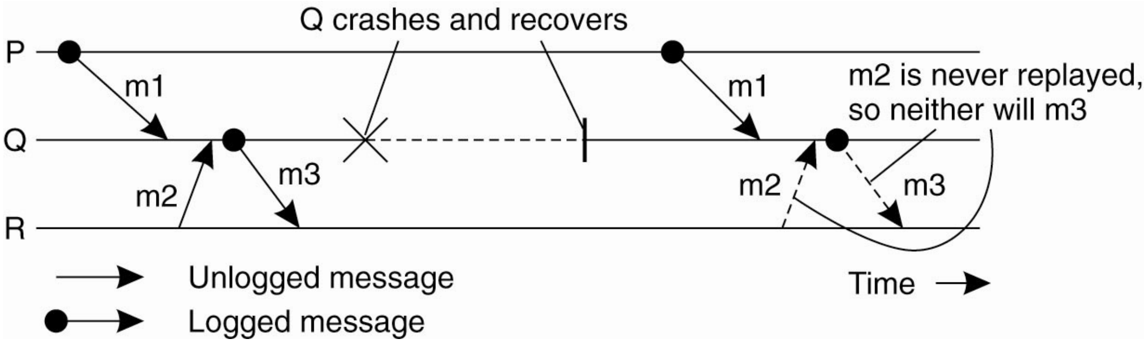
- Independent checkpointing
  - Mayor problem – computing the recovery line
- Coordinated checkpointing
  - Each process takes checkpoint after a globally coordinated action
  - Simple solution: Use a two-phase blocking protocol
    - A coordinator multicasts a *checkpoint request* msg
    - When a participant receives this msg, it takes a checkpoint, stops sending (application) msgs, and reports back that it has taken a checkpoint
    - When all checkpoints have been confirmed at the coordinator, the latter broadcasts a *checkpoint done* msg to allow all processes to continue
- It is possible to consider only processes that depend on the recovery of the coordinator, and ignore the rest

Message logging

- Instead of taking an (expensive) checkpoint, try to replay your (communication) behavior from the most recent checkpoint ⇒ store messages in a log
- 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
- If we record nondeterministic events (for later replay), we obtain a deterministic execution model that will allow a complete replay

Message logging and consistency

- When should we actually log messages?
- Issue: Avoid orphans:
  - Process *Q* has just received and subsequently delivered messages *m1* and *m2*
  - Assume that *m2* is never logged
  - After delivering *m1* and *m2, Q* sends msg *m3* to process *R*
  - Process *R* receives and subsequently delivers *m3*



- We need message logging schemes in which orphans do not occur

Message-logging schemes

- HDR[m] – header of msg contains src, dest, seq #, …
  - All what's needed to resend and deliver it in the correct order
  - A msg m is stable if HDR[m] cannot be lost (in stable storage)
- DEP[m] – set of processes to which m, or another msg causally depending on m, has been delivered
- COPY[m] – set of processes that have a copy of HDR[m] in their volatile memory
- If C is a collection of crashed processes, then Q is an orphan if there's a msg m such that Q in DEP[m] and every process in COPY[m] has crashed (i.e. $\subseteq$ C)
  - That is, it depends on m but there's no way to replay m's transmission

Message-logging schemes

- Goal: No orphans means that for each msg *m,* DEP[m] ⊆ COPY[m]
- Pessimistic protocol: for each non-stable msg m, there is at most one process dependent on m, |DEP[m]| ≤ 1
  - An unstable msg must be made stable before sending another
- Optimistic protocol: for each unstable message *m,* we ensure that if COPY[m] ⊆ *C*, then eventually also DEP[m] ⊆ *C*, where C denotes a set of processes that have been marked as faulty
  - To guarantee that DEP[m] ⊆ *C*, we generally rollback each orphan process *Q until Q* not-in *DEP[m]*

Summary

- Fault tolerant becomes increasingly important for distributed systems
- Redundancy is the key technique to achieve fault tolerance
- With process redundancy, you now need agreement
- And, of course, once a failure has occurred, there’s nothing to do but to recover to a correct state