**CMPSCI 677 Operating Systems** **Spring 2023**

# Lecture 19: April 19

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## 19.1 Fault Tolerance

In single machine systems, if there is a crash, everything fails. In a distributed system, there are multiple nodes. So, the question is how can partial failures be tolerated and recovered from in a distributed system? If a system has $n$ nodes, and the probability that single one fails is $p$, then the probability that there is a failure in the system is given by:

$$p(f) = 1 - p^n$$

As $n$ grows, this number probability converges to 1. In other words, there will almost always be a failed node in a large enough distributed system.

## 19.2 A Perspective and Basic Concepts

We're used to computing systems crashing. Very often we reboot applications or machines in our daily personal life. People who aren't "tech savvy" aren't going to want to do this, or even know how to or that they should. As computing has become more pervasive, we need to make things more reliable.

A system's *dependability* is evaluated based on:

- Availability: The percentage of time for which a system is available. Gold standard is that of the "five nines" i.e a system is available 99.999% of the time. This translates to a few minutes of down-time per year.
- Reliability: System must run continuously without failure.
- Safety: System failures should not compromise safety of client systems and lead to catastrophic failures.
- Maintainability: Systems failures should be easy to fix.

There are many types of faults, including:

- Transient faults: When the system is running, it sees occasional errors but continues to run. The errors come and go, but do not bring the system down.
- Intermittent faults: The system may die occasionally but if you restart it, it comes back up.
- Permanent faults: the system is dead and not coming back up.

| Type of failure | Description |
|---|---|
| Crash failure | A server halts, but is working correctly until it halts |
| Omission failure<br>*Receive omission*<br>*Send omission* | A server fails to respond to incoming requests<br>A server fails to receive incoming messages<br>A server fails to send messages |
| Timing failure | A server's response lies outside the specified time interval |
| Response failure<br>*Value failure*<br>*State transition failure* | The server's response is incorrect<br>The value of the response is wrong<br>The server deviates from the correct flow of control |
| Arbitrary failure | A server may produce arbitrary responses at arbitrary times |

Figure 19.1: Failure models.

The different models of failure are shown in Figure 19.1. Typically fault tolerance mechanisms are assumed to provide safety against crash failures. Arbitrary failures may also be thought to be Byzantine failures where different behaviour is observed at different times. These faults are typically very expensive to provide tolerance against.

### 19.2.1 Redundancy

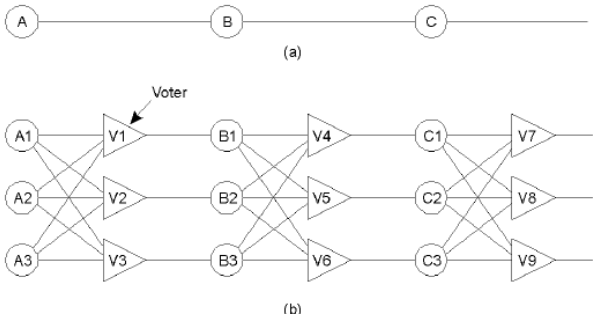



Figure 19.2: Failure masking by redundancy

Fault tolerance may be achieved by means of redundant computations and per stage voting. The circuit shown in Figure 19.2 demonstrates this. Here each computation of the stages A, B and C is replicated and the results are aggregated by votes. This circuit is capable of tolerating one failure per stage of computation. If we try to deal with crash fault, we only need the replication degree to be 2, because we assume the node always produces the correct result if it's alive. We need the replication degree of 3 to deal with Byzantine faults.

**Question**: Why replicate the voter?
*Answer*: Voters can fail. Replicate the voter makes the system more resilient.

**Question**: What if V1 fails and then B2 fails?
*Answer*: If V1 fails, it is not going to get a result and if B1 fails it's going to produce a bad result. The

system can tolerate one failure at a time. It cannot handle a voter and the next component in conjunction with to fail. Parallel failures in multiple stages cannot be handled.

## 19.3 Agreement in Faulty Systems

The two main type of faults are crash failures and Byzantine faults. Fault tolerance during crash failures allows us to deal with servers which crash silently. Detecting failures can be achieved by sending "heartbeat" messages. In a system where we only have silent faults, if the system has $k$ faults simultaneously then we need $k+1$ nodes in total to reach agreement. In Byzantine faults, the server may produce arbitrary responses at arbitrary times. It needs higher degrees of replication to deal with these faults. To detect $k$ byzantine faults, we need $2k + 1$ processes. Byzantine faults are much more difficult to deal with.

**Question**: Is Figure 19.2 for Byzantine or not?
*Answer*: You can do Byzantine with it. Crashes are easy. Crashes can tolerate two faults, but you can do Byzantine as well.

## 19.4 Byzantine Generals Problem

In this case, we are not going to assume the processes are faulty, but rather the network is faulty. The network can either send the message, delete it, or change it.

In the Byzantine generals problem, we have a scenario in which two generals in spatially separated camps want to reach a consensus on whether to attack a fort. The attack will only be successful if both generals attack. They send messengers in order to communicate with each other. Each general sends their vote message containing "attack" or "retreat," and the other general sends an "ack"to the vote. However, the messengers are sometimes killed by the enemy before delivering the message. Therefore, the communication channel is unreliable and both generals do not know if their votes or acks were reliably received. In this set-up, it is provably impossible for the generals to reach a consensus.

For example, suppose the first general sends an "attack" message. The second general receives the message and sends an "ack," but the messenger carrying the "ack" is killed. The first general never receives the ack, so they do not attack. The second general attacks, but the attack fails because the first general does not attack. Suppose instead the second general waits to receive an additional "ack" from the first general before attacking. But suppose the third messenger carrying the second "ack" is killed—now the first general will attack and the second general will not. So instead the first general waits for the second general to send a third "ack"... and so on, ad infinitum. This problem is unsolvable.

Even this is a simplified example, and ignores the possibility of an altered message. The two parties are trying to reach the concept of Common knowledge.

**Question**: Can you reach probabilistic agreement in the Byzantine general problem?

**Answer**: The network of communication in this problem is faulty, thus there is no such thing as probabilistic agreement. This problem cannot be solved if the underlying communication network is faulty.

**Question**: What does it mean to see if the network is reliable?

**Answer**: Messages are delivered and delivered correctly. For example, TCP does that for us. But, we don't know if the generals can be trusted or not.

In the previous example, the network was unreliable. If the communication network is reliable but now there

are $N$ generals and $M$ might be traitors, there is a solution to reach consensus.

Byzantine faults can be modelled as a consensus problem (Byzantine generals problem) among nodes in presence of faulty processes assuming that a Byzantine node will force the system to not reach consensus. A recursive solution to the problem is provided in 19.3 In this, each node collects information from all other nodes and sends it back to all others so that each node now can see the view of the world from the perspective of other nodes. By simple voting, each node can now either accept a single correct value or can identify a Byzantine failure. In a system with $k$ such faults, $2k + 1$ total nodes are needed to only detect that fault is present, while $3k + 1$ total nodes are needed to reach agreement, despite the faults.

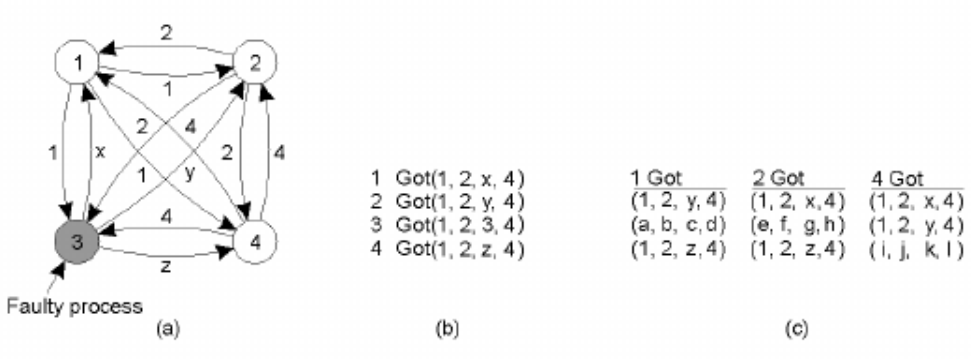



Figure 19.3: Solution to the byzantine general's problem over a reliable communication network.

**Question**: Does Figure 19.3 fail if the number of traitors outnumber the other generals? **Answer**: Yes.

Byzantine faults need a higher degree of replication as stated above to be solved. Thus, handling these kind of faults is expensive.

## 19.5 Reaching Agreement

If message delivery is unbounded, no agreement can be reached even if one process fails and slow processes are indistinguishable from a faulty ones. If the processes are faulty, then appropriate fault models can be used such as BAR fault tolerance where nodes can be Byzantine, altruistic, and rational.

### 19.5.1 Reliable One-To-One Communication

One-one communication involves communication between a client process and a server process whose semantics we have already discussed during RPCs, RMIs, etc. In this we only discussed one-to-one communication, but here we are discussing replication. We need one-to-many communication (multicast or broadcast) in order to reach agreement. We need to extend the one-to-one scenario to the many-to-one scenario in order to solve the agreement problem. Figure 19.4 depicts several failure modes in the one-to-one scenario. These failures can be dealt by (1) Using reliable transport protocols such as TCP (b and d can be dealt with in this manner), or (2) handling failures at the application layer. (a, c and e can be dealt with in this manner)

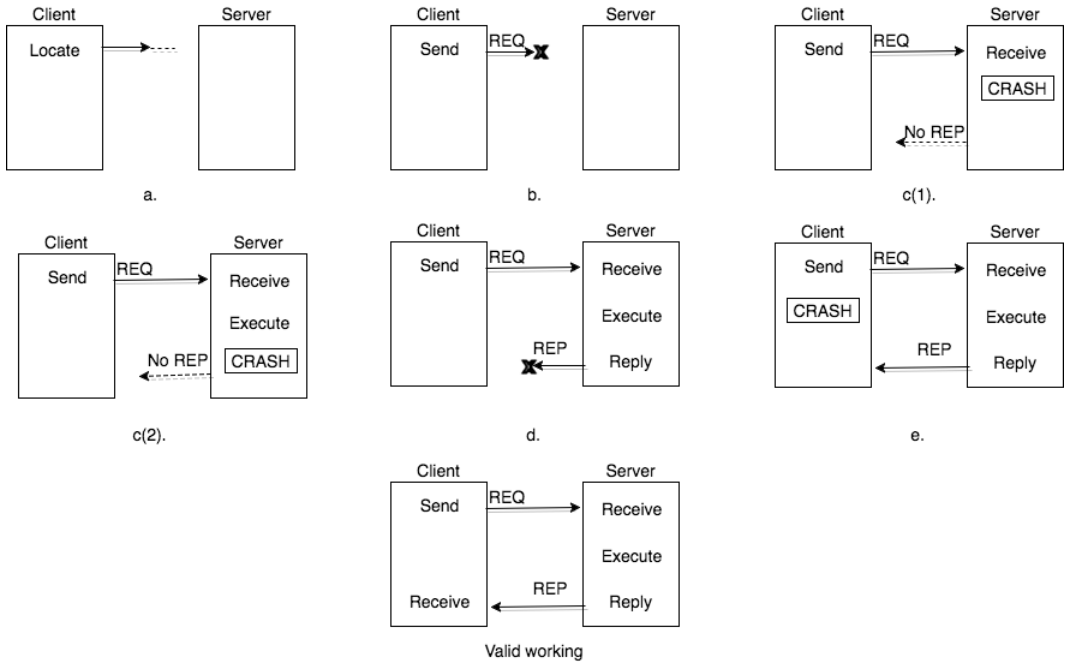



Figure 19.4: Types of failures in the one-to-one scenario. (a) Client unable to locate server. (b) Lost request messages. (c) Server crashes after receiving request. (d) Lost reply messages. (e) Client crashes after sending request.

### 19.5.2 Reliable One-To-Many Communication

Broadcast is sending a message to all nodes in a network. Multicast is sending to a subset of all nodes.

If there are lost messages due to network inconsistencies, we need to retransmit messages after a timeout. There are two ways to do this: ACK-based schemes and NACK-based schemes.

**ACK-based schemes** :

- Send acknowledgement(ACK) for each of the message received. If the sender does not receive the ACK from a receiver, after timeout it retransmits the message.
- Sender becomes a bottleneck: ACK based scheme does not scale well. As number of receivers in the multicast group grows (say 1000 - 10,000) then the number of ACK messages that needs to be processed also grows.
- ACK based retransmission works well for one-one communication but doesnot scale for one-many communication. Large bandwidth gets used in acknowledgment process which results in an **ACK explosion**.

**Question** How to reduce the overhead of ACK in one-many communication?
**Ans.** Instead of sending acknowledgements send negative acknowledgement (NACK).

**NACK-based schemes** :

- NACK-based schemes deals with sender becoming a bottleneck and the ACK-explosion issue.
- ACK indicates a packet was received. NACK indicates a packet was missed.

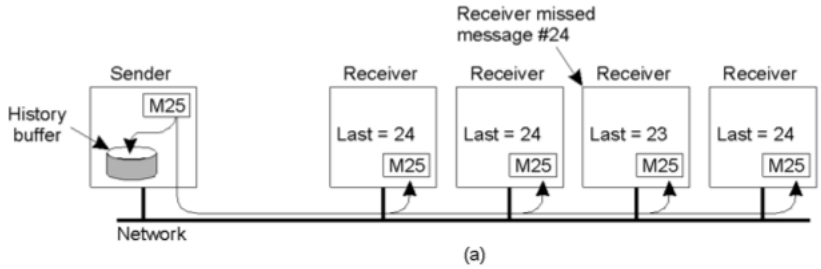



Figure 19.5: Here, all the receivers have their last packet received as #24 except receiver 3 which missed packet #24. Hence, it's last packet is #23. As soon as it receives packet #25, it knows it missed the packet #24.

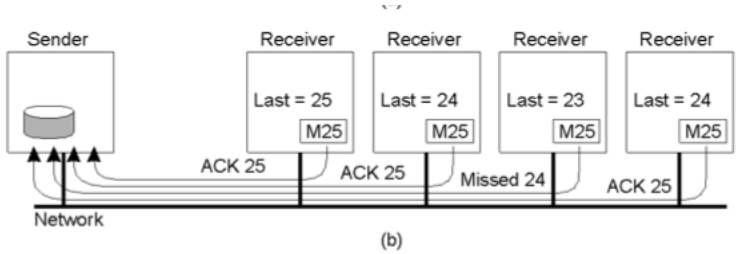



Figure 19.6: Each receiver now sends an acknowledgment ACK either in form of received packet #25 or missed packet #24. As we can see for a single packet, sender receives 'n' ACKs

- Scheme explanation: Send packet to multicast group, if receivers receives a packet, they don't do anything. If receiver sees a missing packet, it sends a NACK to nearby receiver as well as the sender. Sender or neighbouring receivers would re-transmit the missed packet. This optimization works only if the neighboring receivers have the received packets stored in a buffer.
- Sender receive only complaint about the missed packets and this scheme scales well for multicast as the #NACKs received is far less than the #ACKs, unless a massive amount of packet loss.
- Much more scalable than ACK-based schemes

**Question** How does the receiver know that it missed a packet?
**Ans.** Assuming the packets are received in sequence and each packet have a packet number. If receiver sees a gap in the sequence, it knows a packet was missed and sends a NACK.

**Question** Is their a possibility that receive can move from one IP address to another ?
**Ans.** This possibility exists and is true if its one-one or one-many communication. Socket connection breaks if the IP address changes and connection needs to be re-established. The above mentioned schemes does not handle node mobility.

**Question** How to deal with last packet or if sender sends only one packet as receiver may never know if it missed the packet?
**Ans.** Send Dummy packet at the end of transmission and to make sure that dummy packet is acknowledged.

**Question** Is a NACK-based part of TCP protocol or part of the higher level application?
**Ans.** You can ask that question of multicast itself. There are two versions of multicast. IP multicast where an IP address is a group address, and sending to that group IP send to the entire group. That is at the network level. You can also implement this at the application level. The NACK based scheme is mostly done at an application level.

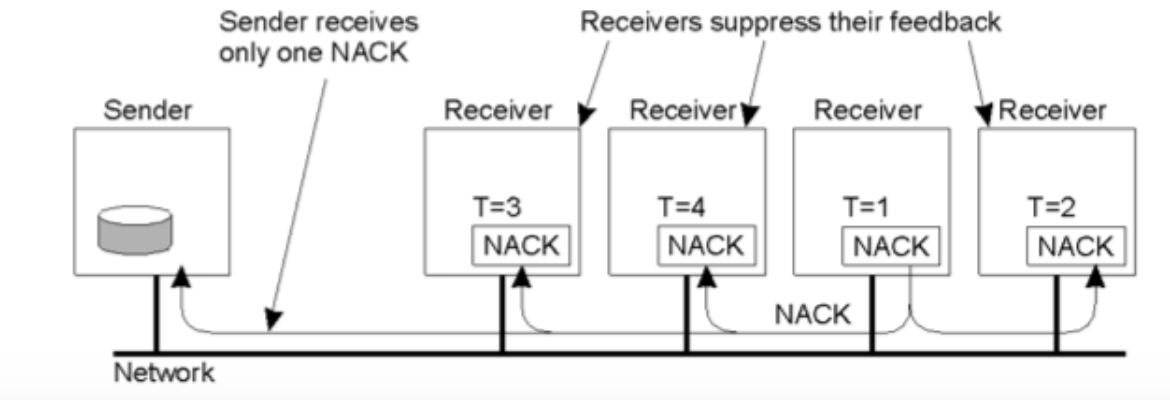



Figure 19.7: Each receiver now suppresses their ACK feedback. Only receiver 3 sends a NACK to other receivers and the sender.

**Question** Can you implement it on top of UDP
**Ans.** Yes. Application level multicast is implemented internally effectively as n unicast messages. Network level is just one socket, and it goes to n receivers.

**Question** Is it like a pub sub architecture?
**Ans.** Not exactly. This is more level than publish and subscribe. This is an abstraction one-to-one communication. You can build publish subscribe on top of this.

This scheme, only addresses how to send a message to all members of the group, it does not discuss other properties of multicast like:

- FIFO order: Messages will be delivered in the same order that they are sent.
- Total order: All processes receive messages in the same order. Total order does not require FIFO.
- Causal order: It is based on the happens before relationship. If send(m1) happens before send(m2), then the receive(m1) should also happen before receive(m2) between processes.

### 19.5.3 Atomic multicast

Atomic multicast guarantees **all or none**. It guarantees that either all processes in a group receive a packet or no process receives a packet.

**Replicated databases** We can't have a scenario where M out of N DB replicas have executed some DB update an the rest haven't. It needs to be ensured that every update to the database is made by all or none.

**Problem** How to handle process crashes in a multicast?

**Solution** Group view: Each message is uniquely associated with a group of processes.

If there is a crash:

- Either every process blocks because 'all' constraint will not be satisfied.
- Or all remaining members need to agree to a group change. The process that crashed is ejected from the group.
- If the process rejoins, it has to run techniques to re-synchronize with the group such that it is in a consistent state.

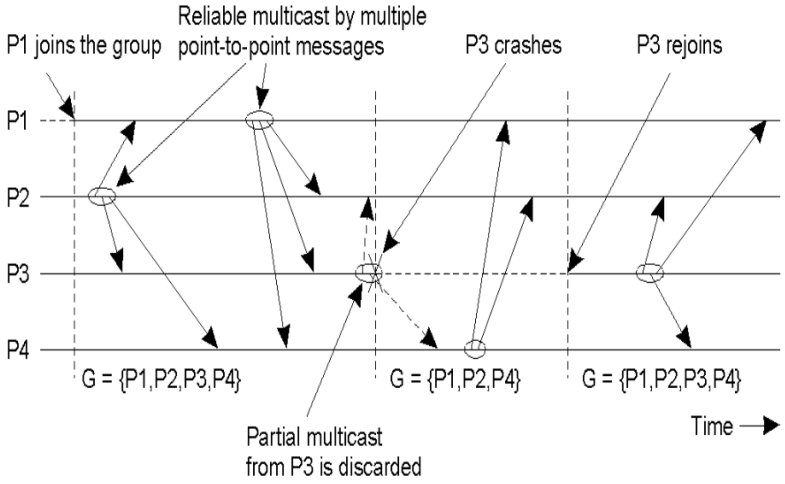



Figure 19.8: Initially all process are up and are part of a group {P1,P2,P3,P4}. All the messages are being reliable multicasted to each of the processes. At dotted line2, P3 crashes while sending a message. From this point onwards, the group {P1,P2,P3,P4} will not maintain the 'all' property of atomic multicast. Hence, P1, P2 and P4 agree on a group change and then start atomic multicast amongst themselves (the new group). At a later point P3 recovers and rejoins. At this point, it run synchronization algorithms to bring itself up-to-date with other members of the group it wants to rejoin.

### 19.5.4 Implementing virtual synchrony

Reliable multicast and atomic multicast are only two ways of implementing virtual synchrony. There are many variants of these techniques as well as other virtual synchrony techniques which may be used in different application based on the requirements of the application.

- Reliable multicast: Deals only with network issues like lost packets or messages. There is no message ordering. NACK based.
- FIFO multicast: Variant of reliable multicast where each sender's message are sent in order. But, there is not guarantee that messages across senders would be ordered as well.
- Causal multicast: Variant of reliable multicast. Causal dependence across messages which are sent in order.
- Atomic multicast: Totally ordered, all or nothing delivery. Deals with process crashes
- FIFO atomic multicast: Variant of atomic multicast.
- Causal atomice multicast: Variant of atomic multicast.

**Question**: Why does atomic multicast have total ordering ?

**Answer**: Atomicity is a stronger property than total order, it is more expensive. Thus the system may as well have total order if it has atomicity.

**Question**: What happens in the scenario where some processes receive the message and other do not receive the message ?

| Multicast | Basic Message Ordering | Total-Ordered Delivery? |
|---|---|---|
| Reliable multicast | None | No |
| FIFO multicast | FIFO-ordered delivery | No |
| Causal multicast | Causal-ordered delivery | No |
| Atomic multicast | None | Yes |
| FIFO atomic multicast | FIFO-ordered delivery | Yes |
| Causal atomic multicast | Causal-ordered delivery | Yes |

Figure 19.9:

**Answer**: There is a difference between receiving or delivering a message and applying/comitting the message. The commit of a message should take place only after consensus in order to ensure safety, this is discussed later on in the lecture.

**Question**: Is causal ordering stricter than FIFO?

**Answer**: Yes, FIFO only ensures ordering within a process whereas, causal ordering ensures ordering across processes.

## 19.6 Distributed commit

Atomic multicast is an example of a more general problem where all processes in a group perform an operation or not at all. Examples:

- Reliable multicast: Operation = Delivery of a message
- Atomic multicast: Operation = Delivery of a message
- Distributed transaction: Operation = Commit transaction

Possible approaches

- Two phase commit (2PC)
- Three phase commit (3PC)

### 19.6.1 Two phase commit

Two phase commit is a distributed commit approach used in database systems which takes into account the agreement of all the processes in a group which have replicated database copies. This approach uses a coordinator and has two phases:

- Voting phase: Processes vote on whether to commit
- Decision phase: Actually commit or abort based on the previous voting phase

The algorithm for this approach can be explained using Fig 19.10.

- The coordinator first prepares or asks all the processes to vote if they want to abort or commit a transaction.
- All the processes vote. If they vote commit, they are ready to listen to the voting results.
- The coordinator collects all replies.
- If all the votes are to commit the transaction, the coordinator asks all processes to commit.
- All processes acknowledge the commit
- In case of even a single abort transaction vote including coordinator process's own abort vote, the coordinator asks all processes to abort.

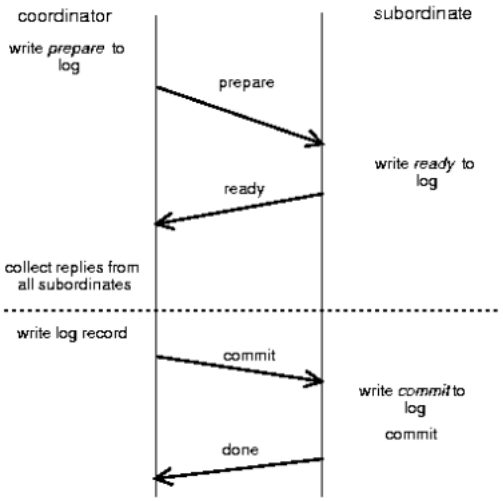



Figure 19.10: Steps showing a successful global commit using 2PC approach

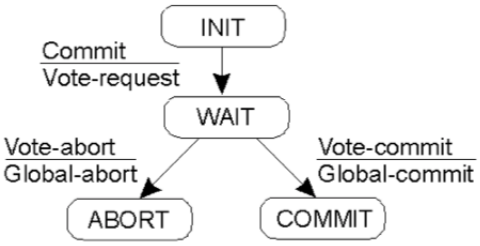



Figure 19.11: **2PC: Coordinator's state transition.** From INIT state, the coordinator asks all processes to vote and goes into WAIT state If any one process votes abort, the coordinator goes to ABORT state and issues global-abort. If all processes vote commit, coordinator goes in COMMIT and issues a global-commit.

**Question** How the coordinator is chosen?
**Ans.** Leader Election.

**Question** If the process is voting for aborting, is the process up/down?
**Ans.** If the process is voting the assumption is that the process is up. If the process is down then there will

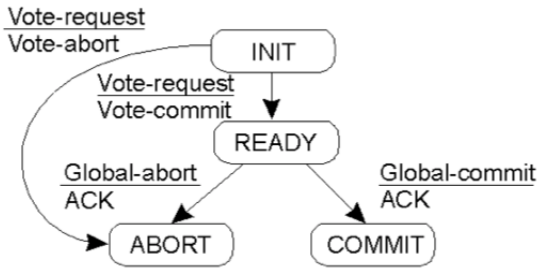



Figure 19.12: **2PC: Subordinate process's state transition.** A process may vote abort and go directly into ABORT state. This is because this single abort would lead to global-abort. A process may vote commit and go into READY state. On being READY and receiving an abort, the process goes into ABORT state. On being READY and receiving a commit, the process goes into COMMIT state.

not be any response. This scheme provides safety property but not liveness property. Drawback of two phase commit process is blocking when the coordinator crashes. If the process crashes, eventually the transaction aborts when the coordinator does not hear back from the process.

**Question** What if it takes long for the process to vote commit?
**Ans.** Process can vote to commit and coordinator makes decision to abort or to commit.

**Question** What if the process is byzantine faulty?
**Ans.** Two phase commit scheme does not work if the process is byzantine faulty. we are assuming crash fault tolerance in both two phase and three phase commit.

**Question** Is the global abort message sent by coordinator?
**Ans.** The result of the vote is always sent by the coordinator in decision phase.

**Question** When the global abort message is sent by coordinator?
**Ans.** If any process vote abort the coordinator sends global abort to all processes.

**Recovering from a crash** : When a process recovers from a crash, it may be in one of the following states:

- INIT: If the process recovers and is in INIT state, then abort locally and inform coordinator. This is safe to do since this process had not voted yet and hence coordinator would be waiting for its vote anyway.
- ABORT: The process being in ABORT state means that coordinator would have issued a global-abort based on the abort vote of this process, hence the process can safely stay in the state it is or move to INIT state.
- COMMIT: The process being in COMMIT state means the coordinator already had issued global commit and this process now can safely stay in this state or move to INIT state.
- READY: The process in this state may be due to a variety of possibilities hence as soon as any process recovers and finds itself in a READY state, it checks other processes for their state to get hint of the group status.
  The table describes the actions of recovered process P on seeing the state of a process Q and the reason for such action.

| State of Q | Action by P | Reason |
|---|---|---|
| COMMIT | Make transition to COMMIT | Any process can be in commit only if coordinator issued a global-commit |
| ABORT | Make transition to ABORT | 2 scenarios:<br>• If process Q has aborted itself. Then coordinator would issue a global-abort. Hence, P can abort.<br>• If process Q aborted because of a global-abort. P can abort in this case too.<br>. |
| INIT | Make transition to ABORT | If process Q is in INIT means it has not voted yet. Thus, voting phase is still going on. Process P can abort safely. |
| READY | Contact another participant | Since, based on process Q's READY state, process P can't infer much. Hence, P should ask another process. |

**If process Q is in READY** : Process Q being in READY state requires a further analysis of action:

- Keep asking other processes about their state
- If at least one of them is not in the READY state then choose an appropriate action from the table above.
- If all of them are in the READY state and are waiting to hear from the coordinator, process P can't make a decision yet. All other processes can't make any decision either.
  **The reason:** Coordinator itself is a participant in the vote, hence, based on the action it takes after recovering, the option decided by the processes as a group may be wrong. That is:
  - All processes can't just commit because coordinator may recover and want to abort.
  - All processes can't just abort because coordinator may recover and see that every process had voted commit and want to commit and issue a global-commit. Other processes in abort state would lead to inconsistent state.

**Problem of 2PC** If the coordinator crashes without delivering the results of a vote, all processes will be deadlocked. This is called **blocking property of 2 phase commit**.

**Question**: If the co ordinator has send messages to some processes and not all and then it crashes then what happens ?

**Answer**: Two properties need to be discussed to **Answer** this, safety and livenss. Safety: Nothing bad happens, the protocol does not reach an incorrect decision. Liveness: There is progress, the protocol reaches a decision. The 2pc guarantees safety and not liveness.

### 19.6.2 Three phase commit

Three phase commit is a variant of two phase commit which takes care of the liveness property that the 2pc could not guarantee in case of coordinator crash.

**How does the $3^{rd}$ phase PRECOMMIT help?** :
Recollecting, blocking problem of 2-phase commit scenario. If a process recovers from a crash and finds

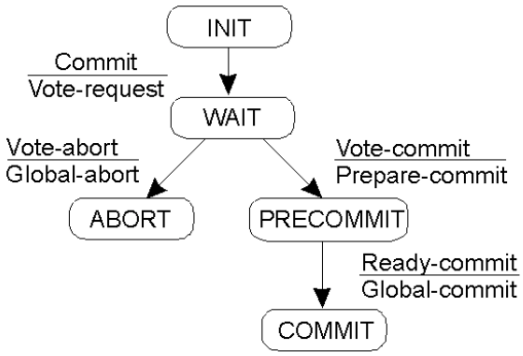
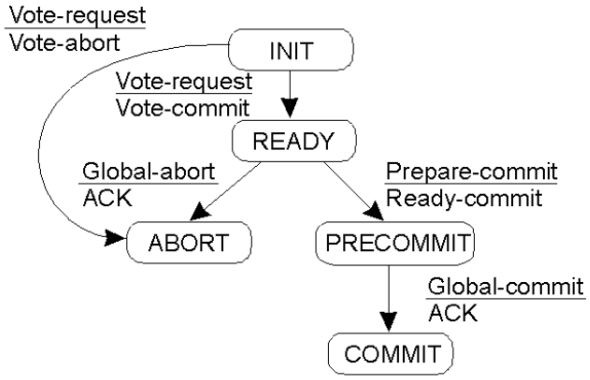



Figure 19.13: **3PC: Coordinator's state transition.** From INIT state, the coordinator asks all processes to vote and goes into WAIT If any process votes abort, the coordinator goes in ABORT and issues global-abort. If all processes vote commit, inform processes to prepare for commit. Go in the PRECOMMIT state. Once all the processes have moved to PRECOMMIT, then issue a global-commit and go into COMMIT state.

itself to be in a READY state, it asks another process about its state. To this the reply is READY state. The processes are still to hear from the coordinator. If every process is in the ready state and the coordinator crashed and can't tell what the outcome of the vote is. A decision can't be made in case of 2PC. However, even in such a scenario a decision can be made safely in case of 3PC. Assuming the coordinator had gone into a PRECOMMIT state and crashed.
The processes can decide among themselves and ABORT.

- If the co-ordinator recovers and finds itself in the PRECOMMIT state, it could ABORT the transaction.
- In 2 phase this could not have been possible because the co-ordinator would have gone into COMMIT phase and rest of the processes would have ABORTed leading to an inconsistent state.

**Question** What happens if co-ordinator crashes after everyone is in pre-commit?
**Ans.** If every process is in PRECOMMIT and not in READY state, they can go ahead and COMMIT. This is because, once co-ordinator recovers, it may ask other processes for the state to which the reply would be COMMIT. This way co-ordinator can go in a COMMIT state as well.




**3PC: Subordinate process's state transition.** A process may vote commit and go into READY state. It may vote abort and go directly into ABORT state. This is because this single abort would lead to global-abort. On being READY and receiving an abort, the process goes into ABORT state. On being READY and receiving a prepare-commit, the process goes into PRCOMMIT state. Once in PRECOMMIT, the processes move to COMMIT state on receiving global-commit.