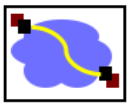
15-440 Distributed Systems

Byzantine Fault Tolerance

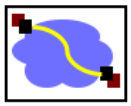
Fault Tolerance



- Terminology & Background
- Byzantine Fault Tolerance (Lamport)
- Async. BFT (Liskov)

2

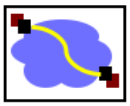
Fault Tolerance



- Being fault tolerant is strongly related to what are called dependable systems. Dependability implies the following:
  - **Availability**: probability the system operates correctly at any given moment
  - **Reliability**: ability to run correctly for a long interval of time
  - **Safety**: failure to operate correctly does not lead to catastrophic failures
  - **Maintainability**: ability to “easily” repair a failed system

3

Failure Models

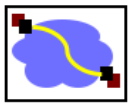


Type of failure	Description
Crash failure	A server halts, but is working correctly until it halts
Omission failure *Receive omission* *Send omission*	A server fails to respond to incoming requests A server fails to receive incoming messages A server fails to send messages
Timing failure	A server's response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

- A system is said to fail if it cannot meet its promises. An error on the part of a system's state may lead to a failure. The cause of an error is called a fault.

4

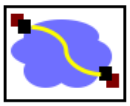
Process Resilience



- Reaching agreement:
  - computation results
  - Electing a leader
  - synchronization
  - committing to a transaction
  - …
- How much replication is necessary?
  - A system is k fault tolerant if it can survive faults in k components and still meet its specifications.

5

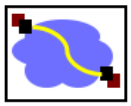
Agreement in Faulty Systems



- Many things can go wrong…
- Communication
  - Message transmission can be unreliable
  - Time taken to deliver a message is unbounded
  - Adversary can intercept messages
- Processes
  - Can fail or team up to produce wrong results
- Agreement very hard, sometime impossible, to achieve!

6

Fault Tolerance



- Terminology & Background
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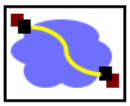
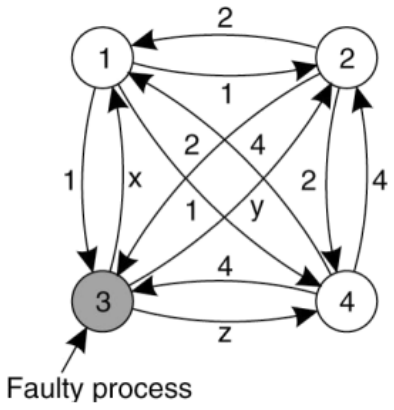
7

Agreement in Faulty Systems - 5



System of N processes, where each process *i* will provide a value v_i to each other. Some number of these processes may be incorrect (or malicious)

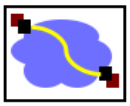
Goal: Each process learn the true values sent by each of the correct processes



The Byzantine agreement problem for three nonfaulty and one faulty process.

8

Byzantine General's Problem

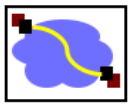


- The Problem: "Several divisions of the Byzantine army are camped outside an enemy city, each division commanded by its own general. After observing the enemy, they must decide upon a common plan of action. Some of the generals may be traitors, trying to prevent the loyal generals from reaching agreement."
- Goal:
  - All loyal generals decide upon the same plan of action.
  - A small number of traitors cannot cause the loyal generals to adopt a bad plan.
- The paper considers a slightly different version from the standpoint of one general (i.e. process) and multiple lieutenants.
- Goal:
  - All loyal lieutenants obey the same order.
  - If the commanding general is loyal, the every loyal lieutenant obeys the order he sends.

Lamport, Shostak, Pease. The Byzantine General's Problem. ACM TOPLAS, 4,3, July 1982, 382-401.

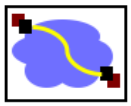
9

What we've learnt so far: tolerate fail-stop failures



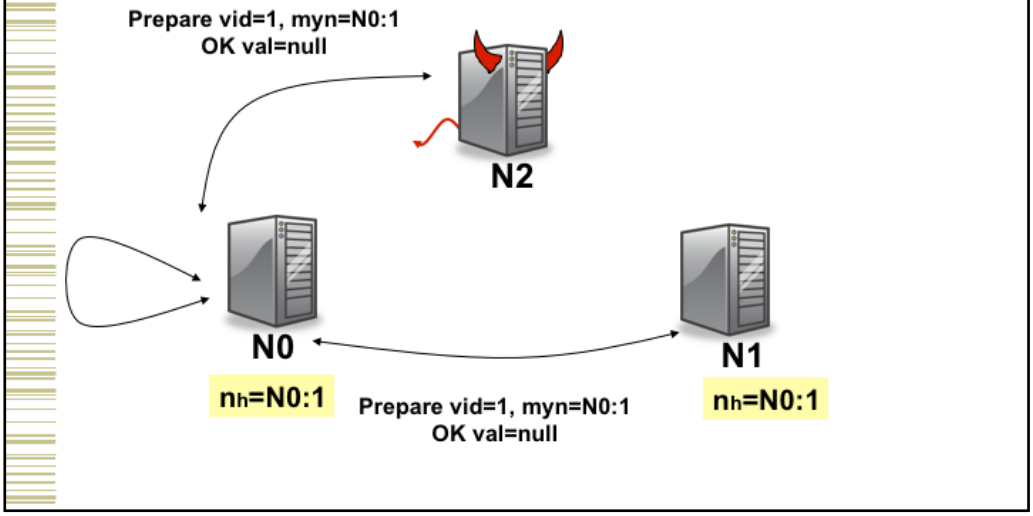
- Traditional RSM tolerates benign failures
  - Node crashes
  - Network partitions
- A RSM w/ 2f+1 replicas can tolerate f simultaneous crashes

Why doesn't traditional RSM work with Byzantine nodes?

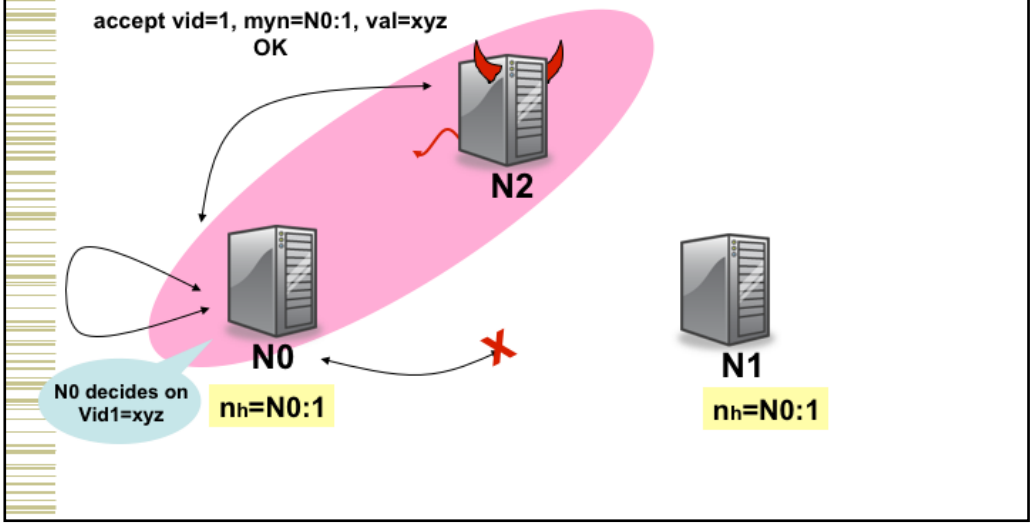


- Cannot rely on the primary to assign seqno
  - Malicious primary can assign the same seqno to different requests!
- Cannot use Paxos for view change
  - Paxos uses a majority accept-quorum to tolerate f benign faults out of 2f+1 nodes
  - Does the intersection of two quorums always contain one honest node?
  - Bad node tells different things to different quorums!
    - E.g. tell N1 accept=val1 and tell N2 accept=val2

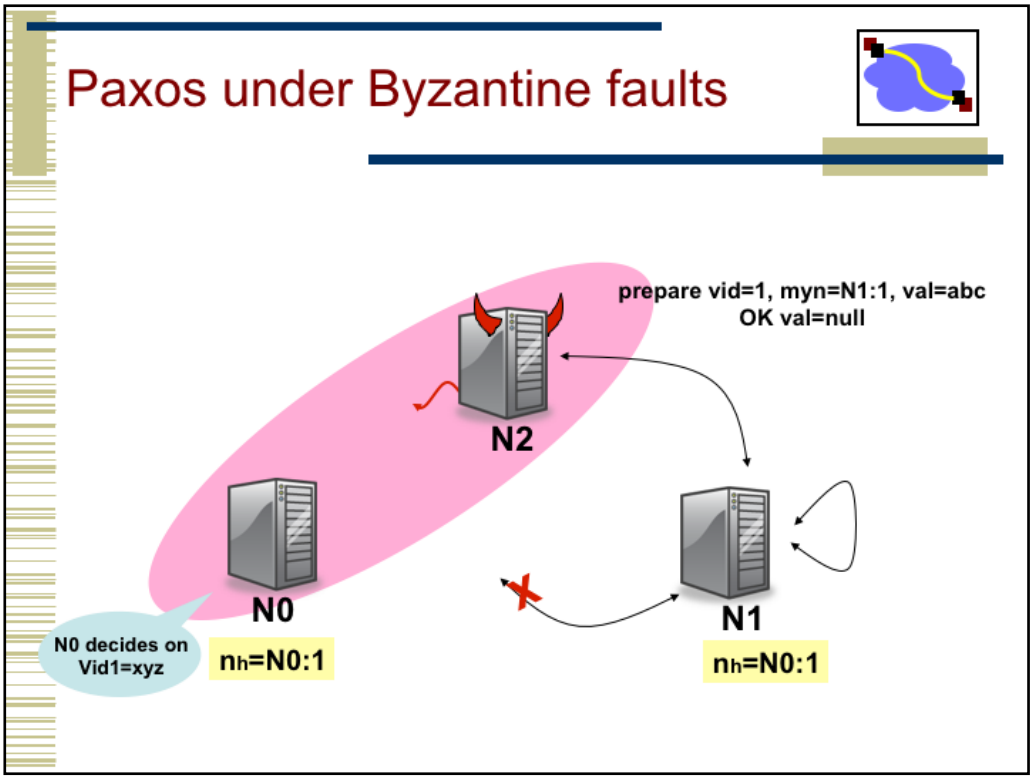
Paxos under Byzantine faults

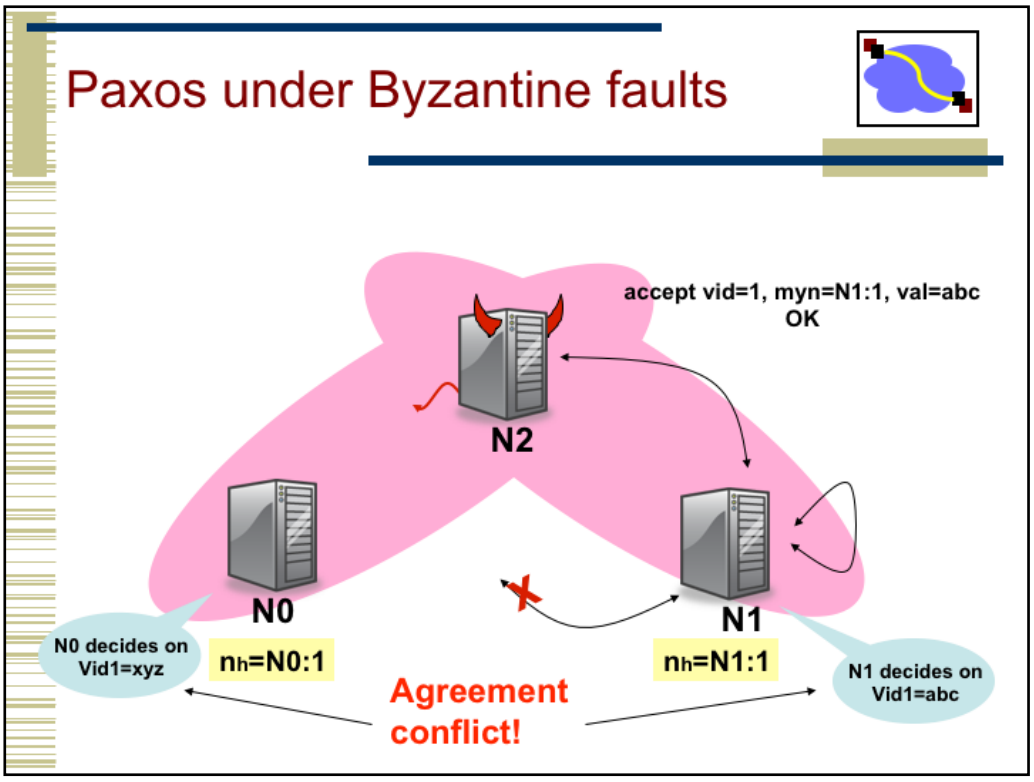


Paxos under Byzantine faults

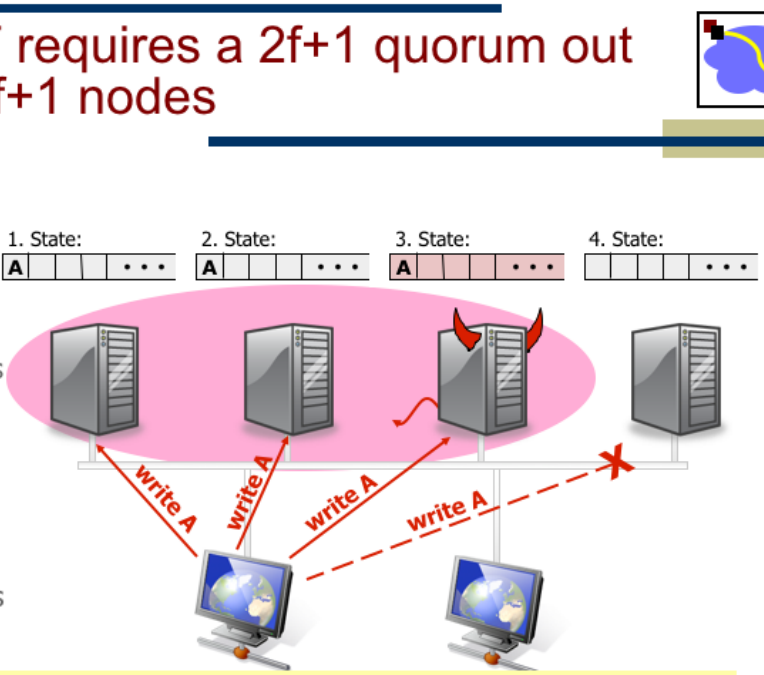


Paxos under Byzantine faults



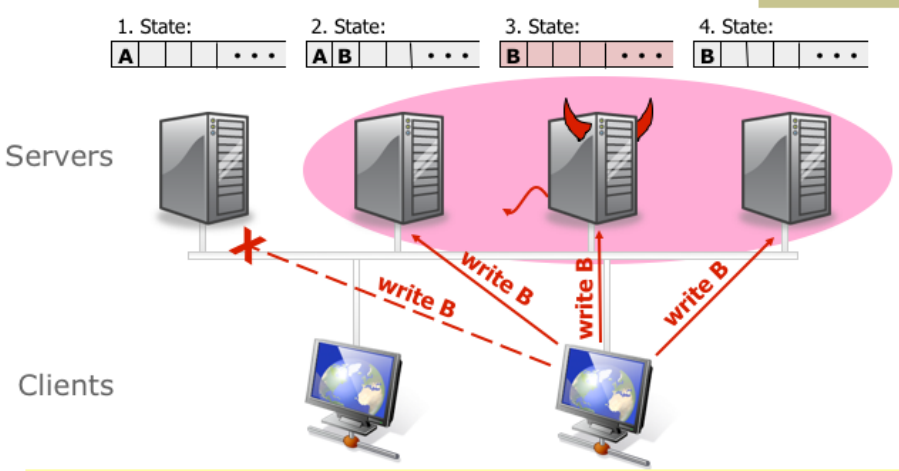

Paxos under Byzantine faults
accept vid=1, myn=N1:1, val=abc
OK
N2
N0
N1
N0 decides on Vid1=xyz
nh=N0:1
nh=N1:1
N1 decides on Vid1=abc
Agreement conflict!

BFT requires a 2f+1 quorum out of 3f+1 nodes

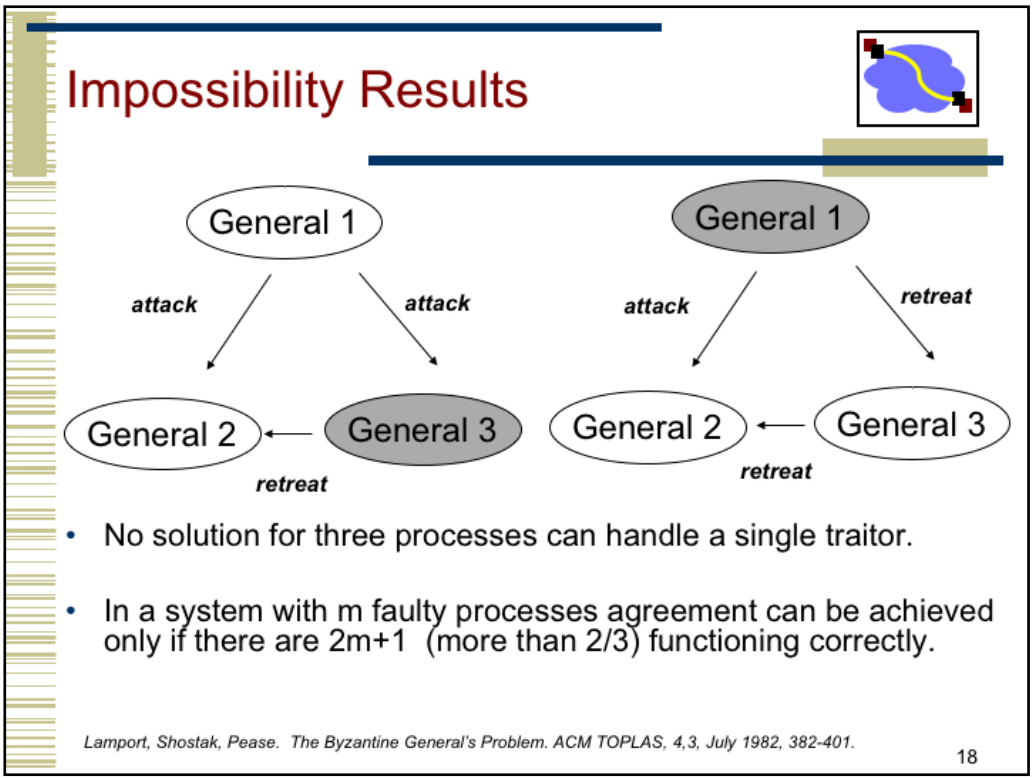


For liveness, the quorum size must be at most N - f

BFT Quorums



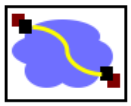
For correctness, any two quorums must intersect at least one honest node: (N-f) + (N-f) - N >= f+1 ➡ N >= 3f+1



The resilience of BFT is optimal: at least 3 *f* + 1 replicas are necessary to provide the safety and liveness properties under our assumptions when up to *f* replicas are faulty. To understand the bound on the number of faulty replicas, consider a replicated service that implements a mutable variable with read and write operations. To provide liveness, the service may have to return a reply before the request is received by more than *n*− *f* replicas, since *f* replicas might be faulty and not responding. Therefore, the service may reply to a write request after the new value is written only to a set *W* with *n* − *f* replicas. If later a client issues a read request, it may receive a reply based on the state of a set *R* with *n*− *f* replicas. *R* and *W* may have only *n*−2 *f* replicas in common. Additionally, it is possible that the *f* replicas that did not respond are not faulty and, therefore, *f* of those that responded might be faulty. As a result, the intersection between *R* and *W* may contain only *n* − 3 *f* nonfaulty replicas. It is impossible to ensure that the read returns the correct value unless *R* and

W have at least one nonfaulty replica in common; therefore *n* > 3 *f* .

Agreement in Faulty Systems

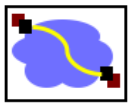


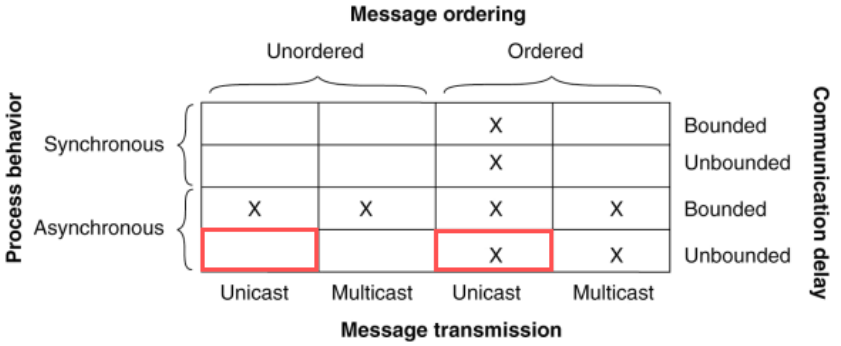
- Possible characteristics of the underlying system:

1. Synchronous versus asynchronous systems.
   - A system is synchronized if the process operation in lock-step mode. Otherwise, it is asynchronous.
2. Communication delay is bounded or not.
3. Message delivery is ordered or not.
4. Message transmission is done through unicasting or multicasting.

19

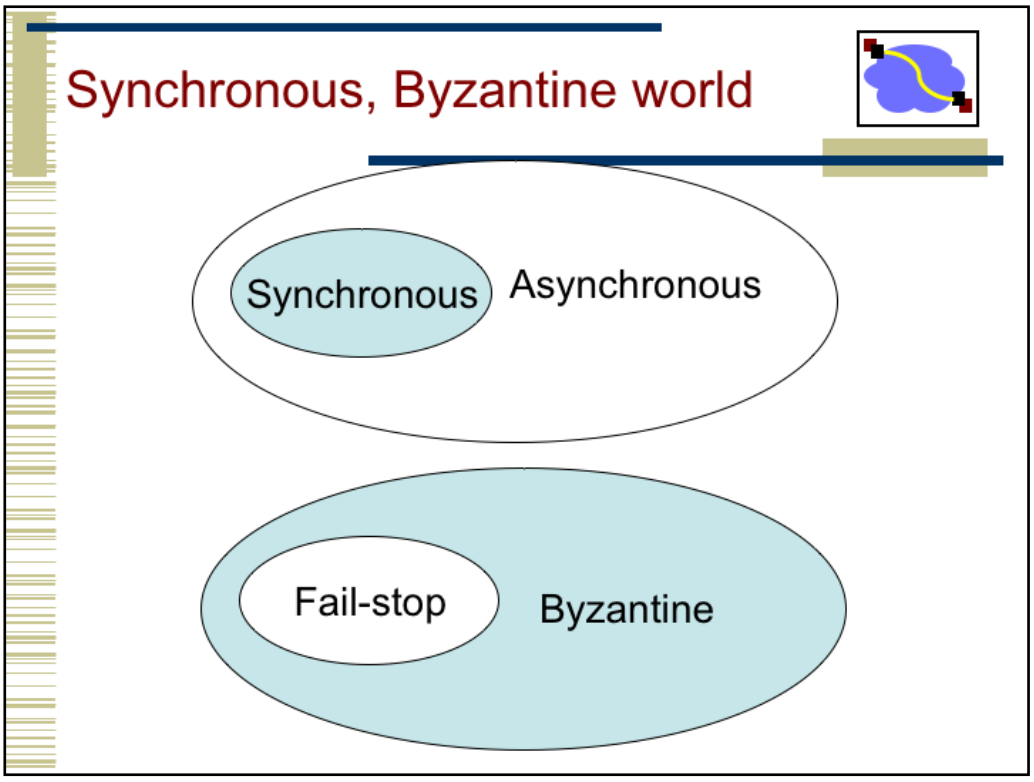
Agreement in Faulty Systems



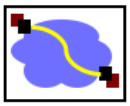


- Circumstances under which distributed agreement can be reached. Note that most distributed systems assume that
  1. processes behave asynchronously
  2. messages are unicast
  3. communication delays are unbounded (see red blocks)

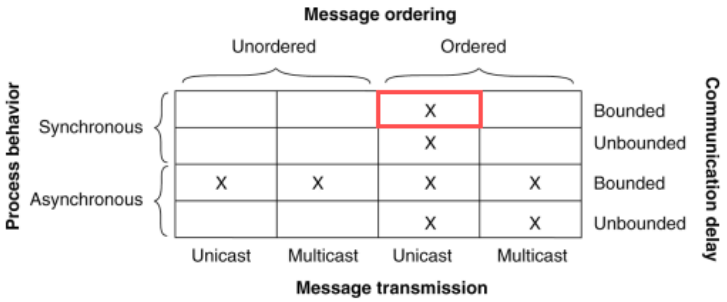
20


Synchronous, Byzantine world
Synchronous
Asynchronous
Fail-stop
Byzantine

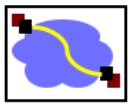
Agreement in Faulty Systems - 4



- Byzantine Agreement [Lamport, Shostak, Pease, 1982]
- Assumptions:
  - Every message that is sent is delivered correctly
  - The receiver knows who sent the message
  - Message delivery time is bounded



Byzantine Agreement Algorithm (oral messages) - 1



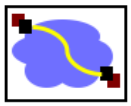
- Phase 1: Each process sends its value to the other processes. Correct processes send the same (correct) value to all. Faulty processes may send different values to each if desired (or no message).

- *Assumptions: 1) Every message that is sent is delivered correctly; 2) The receiver of a message knows who sent it; 3) The absence of a message can be detected.*

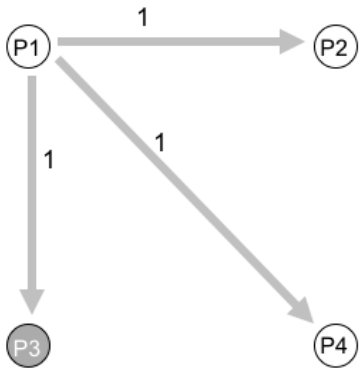
Lamport, Shostak, Pease. The Byzantine General's Problem. ACM TOPLAS, 4,3, July 1982, 382-401.

23

Byzantine General Problem Example - 1

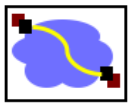


- Phase 1: Generals announce their troop strengths to each other



24

Byzantine General Problem Example - 2



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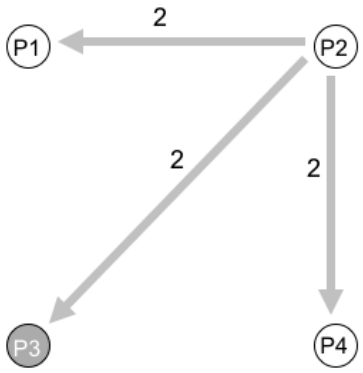
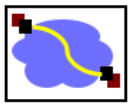


25

Byzantine General Problem Example - 3



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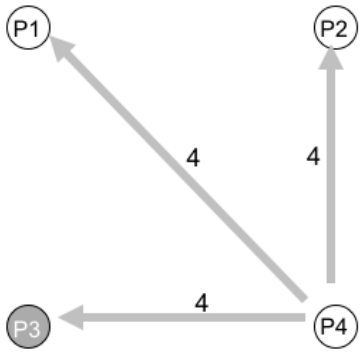
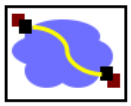


26

Byzantine Agreement Algorithm (oral messages) - 2



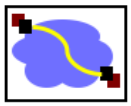
- Phase 2: Each process uses the messages to create a vector of responses – must be a default value for missing messages.

- *Assumptions: 1) Every message that is sent is delivered correctly; 2) The receiver of a message knows who sent it; 3) The absence of a message can be detected.*

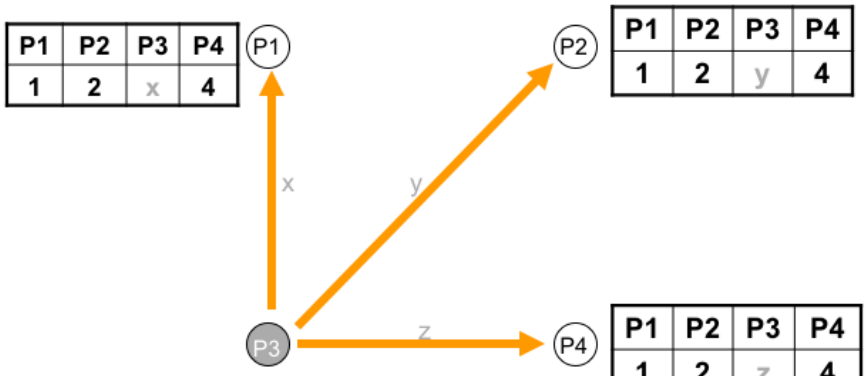
Lamport, Shostak, Pease. The Byzantine General's Problem. ACM TOPLAS, 4,3, July 1982, 382-401.

27

Byzantine General Problem Example - 4

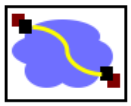


- Phase 2: Each general construct a vector with all troops



28

Byzantine Agreement Algorithm (oral messages) - 3



- Phase 3: Each process sends its vector to all other processes.
- Phase 4: Each process the information received from every other process to do its computation.

- *Assumptions: 1) Every message that is sent is delivered correctly; 2) The receiver of a message knows who sent it; 3) The absence of a message can be detected.*

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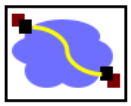
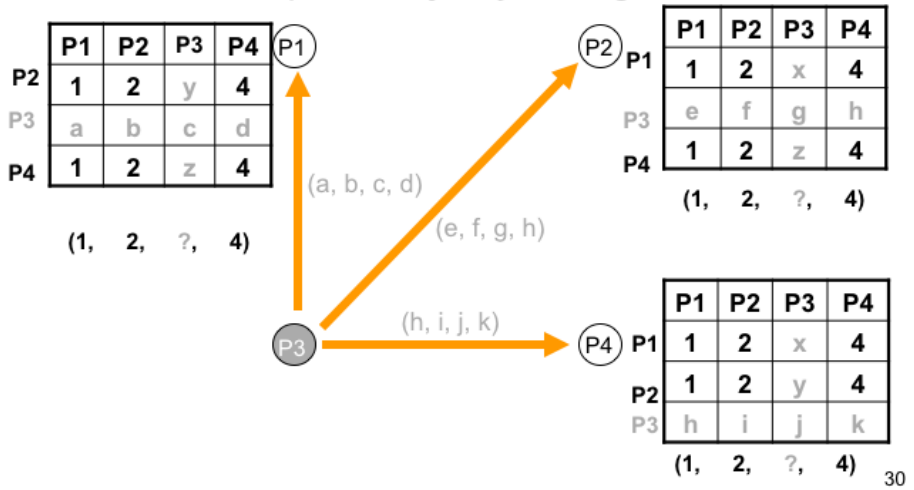
29

Byzantine General Problem Example - 5

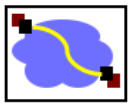


- Phase 3,4: Generals send their vectors to each other and compute majority voting



30

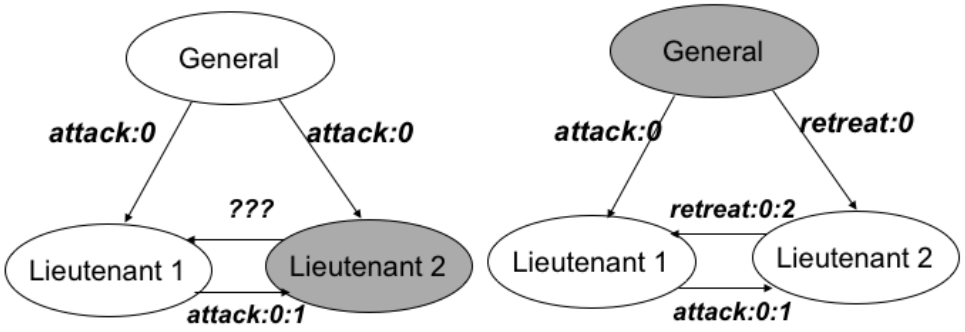
Byzantine Agreement Algorithm (signed messages)



- Adds the additional assumptions:
  - A loyal general's signature cannot be forged and any alteration of the contents of the signed message can be detected.
  - Anyone can verify the authenticity of a general's signature.
- Algorithm SM(m):
- The general signs and sends his value to every lieutenant.
- For each i:
  - If lieutenant i receives a message of the form v:0 from the commander and he has not received any order, then he lets Vi equal {v} and he sends v:0:i to every other lieutenant.
  - If lieutenant i receives a message of the form v:0:j1:…:jk and v is not in the set Vi then he adds v to Vi and if k < m, he sends the message v:0:j1:…:jk:i to every other lieutenant other than j1,…,jk
  - For each i: When lieutenant i will receive no more messages, he obeys the order in choice(Vi).
- Algorithm SM(m) solves the Byzantine General's problem if there are at most m traitors.

Lamport, Shostak, Pease. The Byzantine General's Problem. ACM TOPLAS, 4,3, July 1982, 382-401.

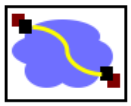
Signed messages



SM(1) with one traitor

Lamport, Shostak, Pease. The Byzantine General's Problem. ACM TOPLAS, 4,3, July 1982, 382-401.

Fault Tolerance



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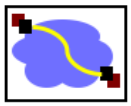
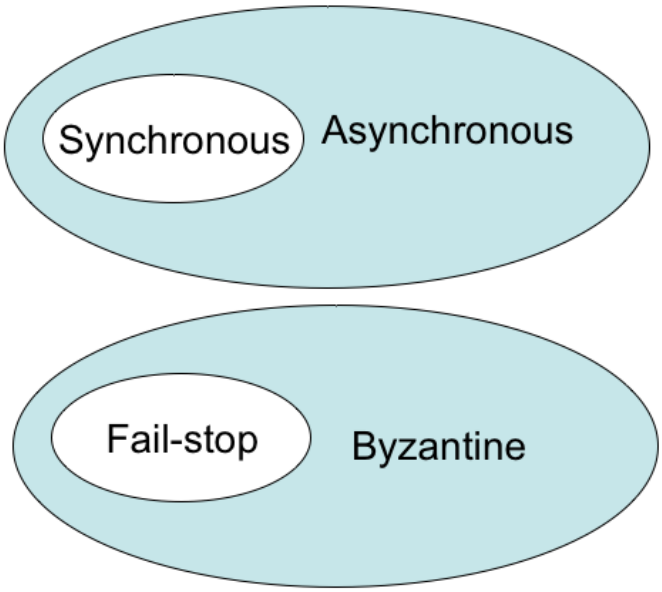
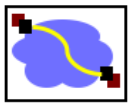
33

Practical Byzantine Fault Tolerance:Asynchronous, Byzantine





Practical Byzantine Fault Tolerance



- Why async BFT? BFT:
  - Malicious attacks, software errors
  - Need N-version programming?
  - Faulty client can write garbage data, but can't make system inconsistent (violate operational semantics)
- Why async?
  - Faulty network can violate timing assumptions
  - But can also prevent liveness

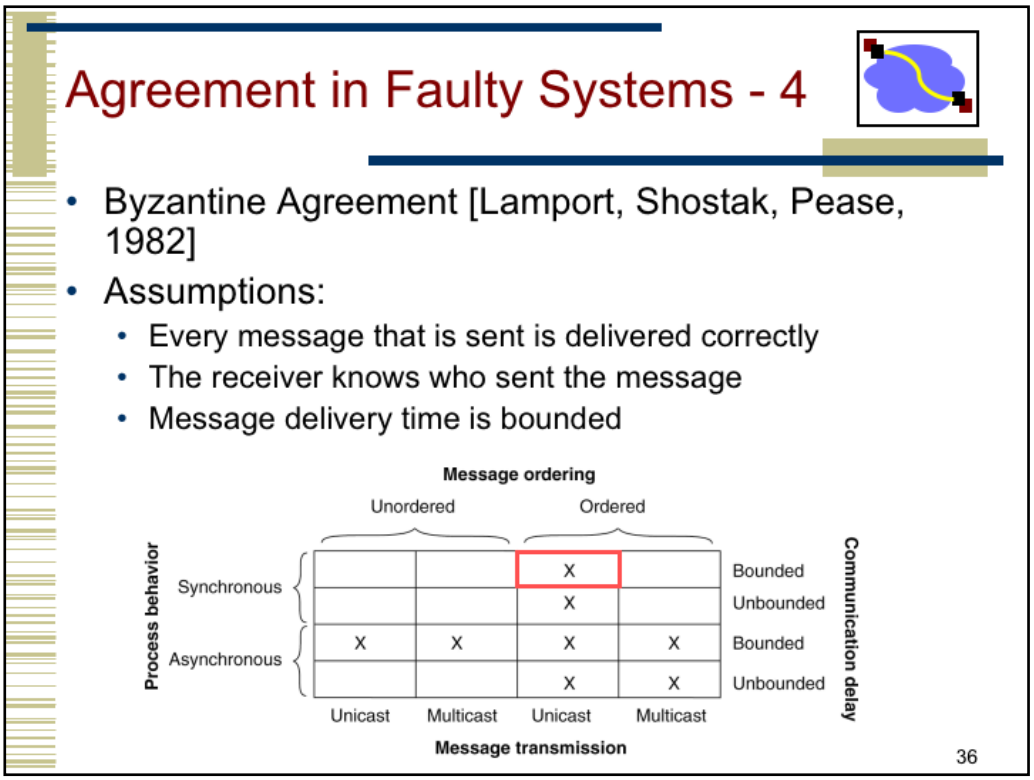
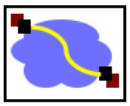


Table is from http://csis.pace.edu/~marchese/CS865/Papers/Turek-ManyFacesOfConsensus.pdf

In the system Fischer, Lynch, and Paterson studied, messages were unordered, communication was unbounded, and processors were asyn- chronous.

Distributed systems



- FLP impossibility: Async consensus may not terminate
  - Sketch of proof: System starts in "bivalent" state (may decide 0 or 1). At some point, the system is one message away from deciding on 0 or 1. If that message is delayed, another message may move the system away from deciding.
  - Holds even when servers can only crash (not Byzantine)!
  - Hence, protocol cannot always be live (but there exist randomized BFT variants that are probably live)

[See Fischer, M. J., Lynch, N. A., and Paterson, M. S. 1985. Impossibility of distributed consensus with one faulty process. J. ACM 32, 2 (Apr. 1985), 374-382.]

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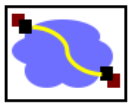
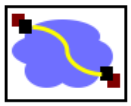
PBFT ideas



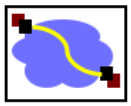
- PBFT, “Practical Byzantine Fault Tolerance”, M. Castro and B. Liskov, SOSP 1999
- Replicate service across many nodes
  - Assumption: only a small fraction of nodes are Byzantine
  - Rely on a super-majority of votes to decide on correct computation.
  - Makes some weak synchrony (message delay) assumptions to ensure liveness
    - Would violate FLP impossibility otherwise
- PBFT property: tolerates <=f failures using a RSM with 3f+1 replicas

PBFT main ideas



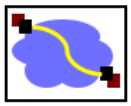
- Static configuration (same 3f+1 nodes)
- To deal with malicious primary
  - Use a 3-phase protocol to agree on sequence number
- To deal with loss of agreement
  - Use a bigger quorum (2f+1 out of 3f+1 nodes)
- Need to authenticate communications

PBFT Strategy



- Primary runs the protocol in the normal case
- Replicas watch the primary and do a view change if it fails

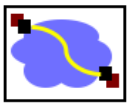
Replica state



- A replica id i (between 0 and N-1)
  - Replica 0, replica 1, …
- A view number v#, initially 0
- Primary is the replica with id

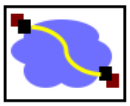
  i = v# mod N
- A log of <op, seq#, status> entries
  - Status = pre-prepared or prepared or committed

Normal Case



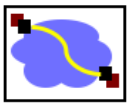
- Client sends request to primary
  - or to all

Normal Case



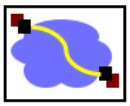
- Primary sends pre-prepare message to all
- Pre-prepare contains <v#,seq#,op>
  - Records operation in log as pre-prepared
  - Keep in mind that primary might be malicious
    - Send different seq# for the same op to different replicas
    - Use a duplicate seq# for op

Normal Case



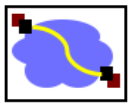
- Replicas check the pre-prepare and if it is ok:
  - Record operation in log as pre-prepared
  - Send prepare messages to all
  - Prepare contains <i,v#,seq#,op>
- All to all communication

Normal Case:



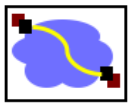
- Replicas wait for 2f+1 matching prepares
  - Record operation in log as prepared
  - Send commit message to all
  - Commit contains <i,v#,seq#,op>
- What does this stage achieve:
  - All honest nodes that are prepared prepare the same value
  - At least f+1 honest nodes have sent prepare/pre-prepare

Normal Case:



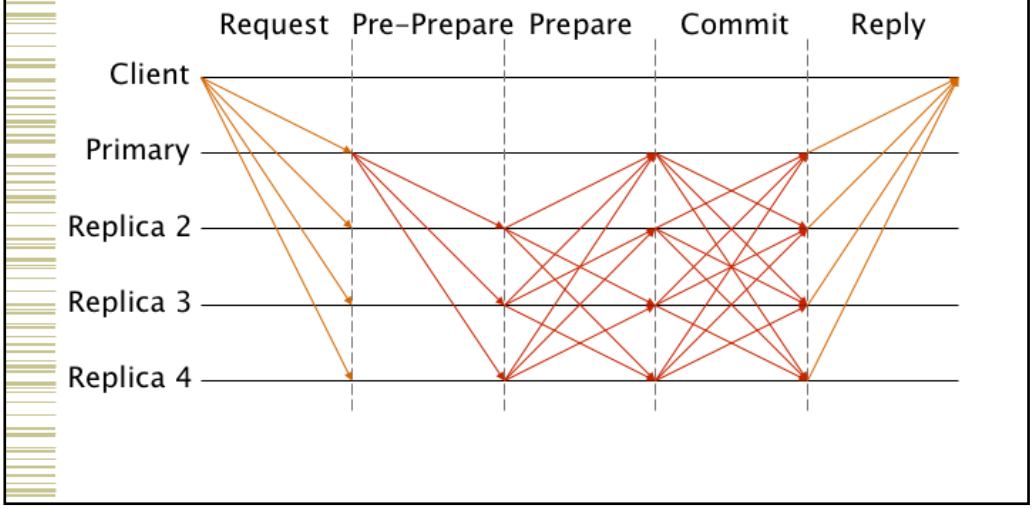
- Replicas wait for 2f+1 matching commits
  - Ensures that at least f+1 trustworthy nodes have committed
- Record operation in log as committed
  - Execute the operation
  - Send result to the client

Normal Case

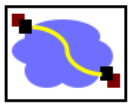


- Client waits for f+1 matching replies
  - Ensures at least one node has committed and executed

PBFT


Request
Pre-Prepare
Prepare
Commit
Reply
Client
Primary
Replica 2
Replica 3
Replica 4

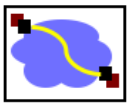
View Change



- Replicas watch the primary
- Request a view change

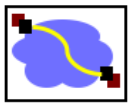
- Commit point: when 2f+1 replicas have prepared

View Change



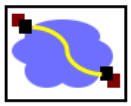
- Replicas watch the primary
- Request a view change
  - send a do-viewchange request to all
  - new primary requires 2f+1 requests to accept new role
  - sends new-view with proof that it got the

Additional Issues



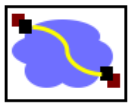
- State transfer
- Checkpoints (garbage collection of the log)
- Selection of the primary
- Timing of view changes

Possible improvements



- Lower latency for writes (4 messages)
  - Replicas respond at prepare
  - Client waits for 2f+1 matching responses
- Fast reads (one round trip)
  - Client sends to all; they respond immediately
  - Client waits for 2f+1 matching responses

Practical limitations of BFTs



- Expensive
- Protection is achieved only when <= f nodes fail
- Does not prevent many types of attacks:
  - Turn a machine into a botnet node
  - Steal SSNs from servers