# Distributed Systems

EECE 513: Design of Fault-tolerant Digital Systems

# Outline

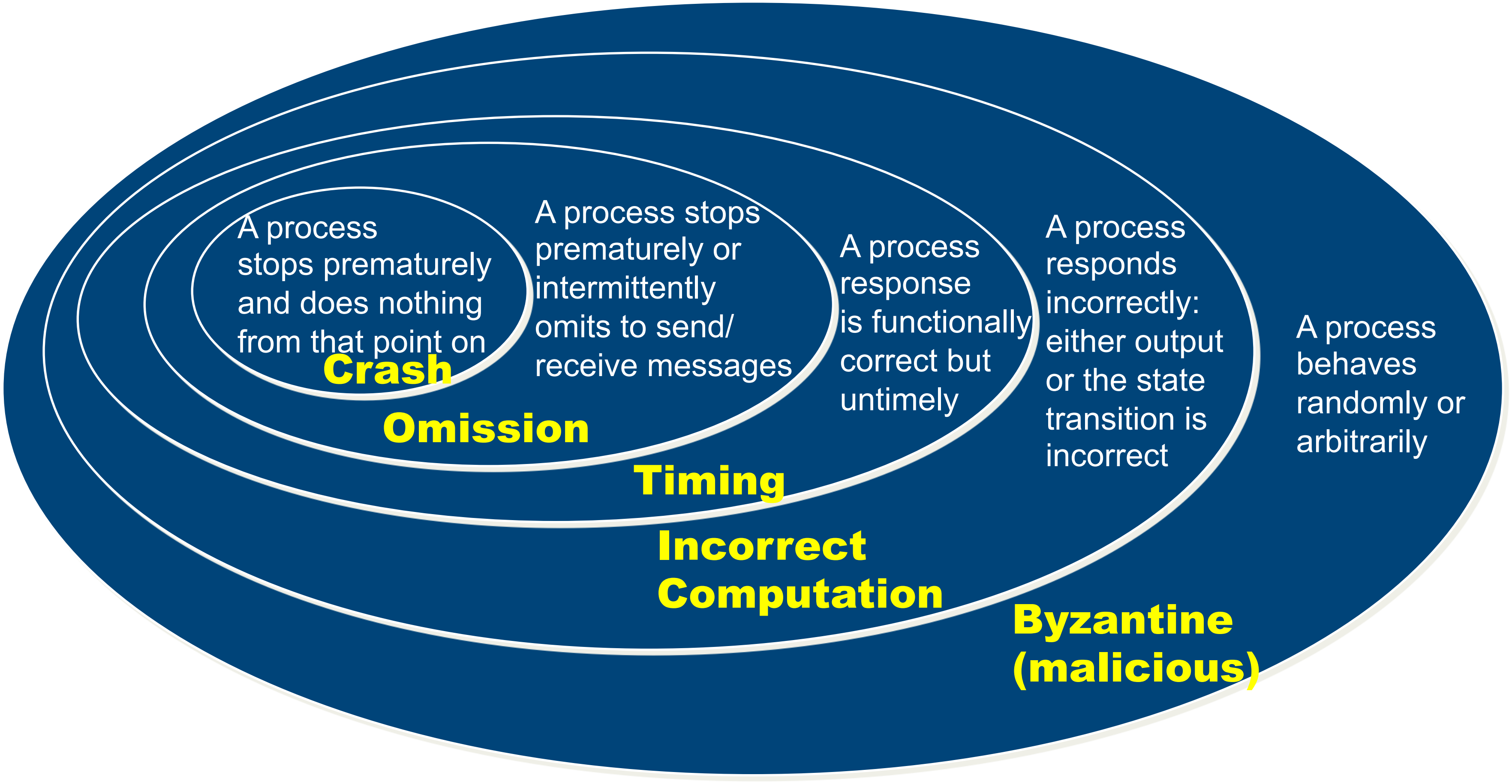
- Issues in design of distributed systems
- Agreement protocols
- Byzantine agreement algorithm
- Paxos

# Distributed Systems: Questions

***How do we integrate components with varying fault tolerance characteristics into a coherent high availability distributed system?***

- ***How do you guarantee reliable communication (message delivery)?***
- ***How do you synchronize actions of dispersed processors and processes?***
- ***How do you make sure that replicated services (independently executing) have a consistent view of the overall networked system?***
- ***How do you contain errors (or achieve fail-silent behavior of components) to prevent error propagation?***
- ***How do you adapt the system architecture to changes in availability requirements of the application(s)?***

# Fault Models



# What Do We Need ?

- Understand and provide solution to *replication problem* (in its broad meaning)
  - process/data replication
  - replica consistency and replica determinism
  - replica recovery/reintegration
  - redundancy management
- Provide efficient techniques for supporting a consistent data and coherent behavior between system components despite failures

# Agreement Protocols

- **It is often required that processes reach a mutual agreement.**
- **Faulty processes can send conflicting values to other processors preventing them from reaching an agreement**
- **Processes must exchange their values and relay the values received from other processes several times to isolate the effects of faulty processes.**

- **System model**
  - There are *n* processes in the system and at most *m* of them can be faulty.
  - Processes communicate with one another by message passing and the receiver process always knows the identity of the sender process
  - The communication network is reliable, i.e., only processes can fail

# Synchronous vs. Asynchronous

- In ***synchronous computation***, processes in the system run in lockstep:
  - In each step, a process receives messages (sent to it in the previous step), performs computation, and sends messages to other processes (received in the next step).
  - A process knows all the messages it expects to receive in a step/round
- In ***asynchronous computation***, processes do not execute in lockstep:
  - A process can send and receive messages and perform computation at any time
  - Agreement is impossible with even a single, faulty process – FLP result by Lynch et al.
- The **synchronous model** of computation is assumed

# Model of Processor Failures

- **Crash fault**: Processor stops functioning and never resumes operation
- **Omission fault**: Processor “omits” to send messages to some processors
- **Byzantine fault**: Processor behaves randomly and arbitrarily

In synchronous model, omission can be detected. We assume Byzantine model.

# Authenticated vs. Non-Authenticated Messages

- To reach an agreement, processes need to exchange their values and relay the received values to other processors

**Two Types of Messages:**

- ***Authenticated (signed)***
  - A faulty process cannot forge a message or change the contents of a received message (before it relays the message to other processes).
  - A process can verify the authenticity of the received message.
- ***Non-authenticated (oral)***
  - A faulty process can forge a message and claim to have received it from another processor or change the contents of the received message before it relays it to other processes.
  - A process has no way to verify the authenticity of the received message.

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# Agreement Problems - Classification

- ***The Byzantine Agreement Problem***
  - **A single value** is **initialized by any arbitrary process,** and all non-faulty processes have to agree on that value

- ***The Consensus Problem***
  - Every process has its **own initial value,** and all correct processes must agree on **a single, common value.**

- ***The Interactive Consistency Problem***
  - Every process has its **own initial value,** and all non-faulty process must agree on **a set of common values.**

# The Byzantine Agreement Problem

- An **arbitrarily chosen process** - *the source* - broadcasts its value to all other processes.

- ***Agreement*** - All non-faulty processes agree on the same value

- ***Validity*** - If the source process is non-faulty then the common value agreed on by all non-faulty processes should be the value of the source

# The Consensus Problem

- **Every process** broadcasts its initial value to all other processes
  - *Initial values of the processes may be different.*

- ***Agreement*** - All non-faulty processes agree on the same single value.

- ***Validity*** - if the initial value of every non-faulty process is $\upsilon$, then the common value agreed upon by non-faulty processes must be $\upsilon$.

# The Interactive Consistency Problem

- **Every process** broadcasts its initial value to all other processes
  - *Initial values of the processes may be different.*

- ***Agreement*** - All non-faulty processes agree on the same vector:
  $(\upsilon_1, \upsilon_2, \ldots, \upsilon_n)$

- ***Validity*** - If the $i_{th}$ process is non-faulty and its initial value is $\upsilon_i$, then the $i_{th}$ value to be agreed on by all non-faulty processes must be $\upsilon_i$

# Relations Among the Agreement Problems

1. Given an algorithm to solve Byzantine agreement, how would you solve Interactive Consistency?
2. Given an algorithm to solve Interactive Consistency, how would you solve Consensus?
3. Given an algorithm to solve Consensus, how would you solve Byzantine Agreement?

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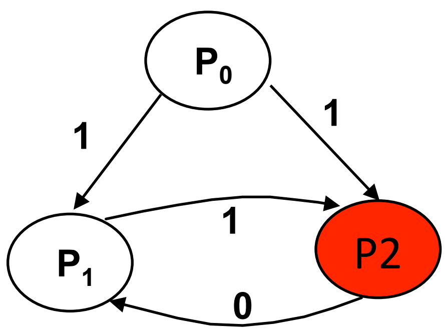
# Byzantine Agreement Problem

- In a fully connected network it is impossible to reach a consensus if the number of faulty processes, *m* , exceeds $\lfloor (n-1)/3 \rfloor$ ,
  - For example, if $n = 3$, than $m = 0$, i.e., having three processes, we cannot solve the Byzantine agreement problem n the event of a single error.
  - The protocol requires *m+1 rounds of message exchange* (*m* is the maximum number of faulty processes)
  - This is also the lower bound on the number of rounds of message exchanged.
- Using authenticated messages, this bound is relaxed, and a consensus can be reached for any number of faulty processes.
  - We assume non-authenticated messages in the rest of the discussion

# Impossibility Results

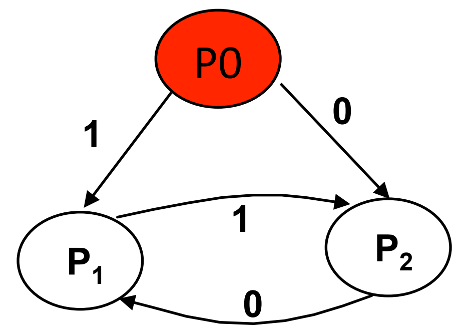
- Consider a system with three processes $p_1$, $p_2$, $p_3$
- There are two values, 0 and 1, on which processes agree.
- $p_0$ initiates the algorithm.

**Case one - $p_0$ is not faulty**




assume $p_2$ is faulty
suppose $p_0$ broadcast 1 to $p_1$ and $p_2$
$p_2$ acts maliciously and sends 0 to $p_1$
$p_1$ must agree on 1 if algorithm is to be satisfied
$p_1$ receives two conflicting values
**no agreement is possible**

**Case one - $p_0$ is faulty**




suppose $p_0$ sends 1 to $p_1$ and 0 to $p_2$
$p_2$ communicates 0 to $p_1$
$p_1$ receives two conflicting values
**no agreement is possible**

# Oral Messages Algorithm OM(m)

- A recursive algorithm solves the Byzantine agreement problem for >= **3m+1** processes in the presence of at most ***m*** faulty processes.

**Algorithm OM(0)**

- 1. The source process sends its value to every process,
- 2. Each process uses the value it receives from the source (if it receives no value, then it uses a default value of 0).

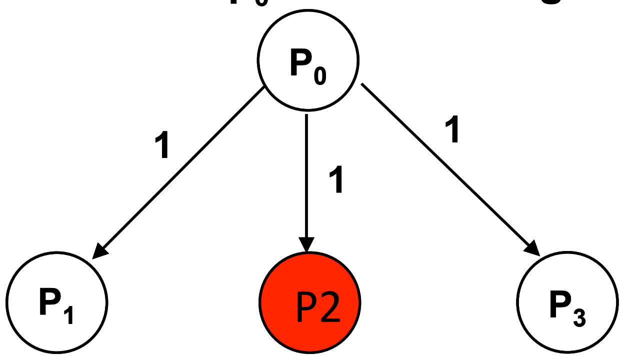
# Oral Messages Algorithm OM(m)

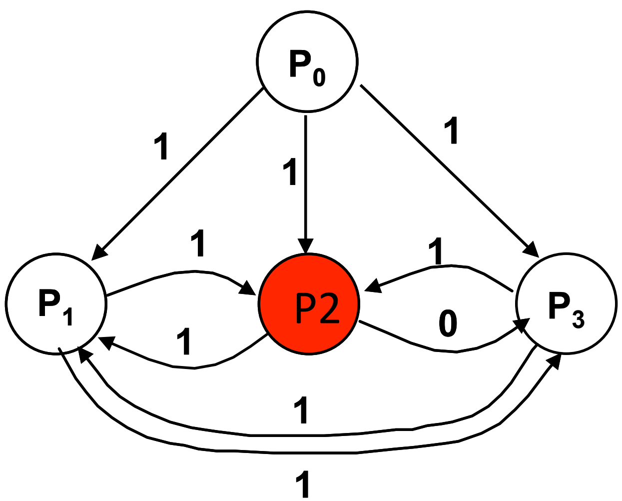
**Algorithm OM(m), m > 0**

1. The source process sends its value to every process,
2. For each *i*, let $\upsilon_i$ be the value processor *i* receives from the source,
   - Process *i* acts as a new source and initiates ***Algorithm OM(m-1)*** wherein it sends the value $\upsilon_i$ to each of the n-2 other processes
3. For each *i* and each $j \neq i$ let $\upsilon_j$ be the value process *i* received from *j* in step (2) using *Algorithm OM(m-1).* (If no value is received then default value 0 is used ). Process *i* uses the value *majority* $(\upsilon_1, \upsilon_2, \ldots, \upsilon_{n-1})$.

# Oral Messages Algorithm OM(m)

**Consider a system with four processes $p_0$, $p_1$, $p_2$, $p_3$**
**$p_0$ initiate the algorithm; $p_2$ is faulty**




**To initiate the agreement $p_0$ executes OM(1) wherein it sends 1 to all processes**

**At step 2 of the OM(1) algorithm, $p_1$, $p_2$, $p_3$ execute the algorithm OM(0)**

**$p_1$ and $p_3$ are non-faulty and**
**$p_1$ sends 1 to $\{p_2, p_3\}$**
**$p_3$ sends 1 to $\{p_1, p_2\}$**
**$p_2$ is faulty and sends 1 to $p_1$ and 0 to $p_3$**

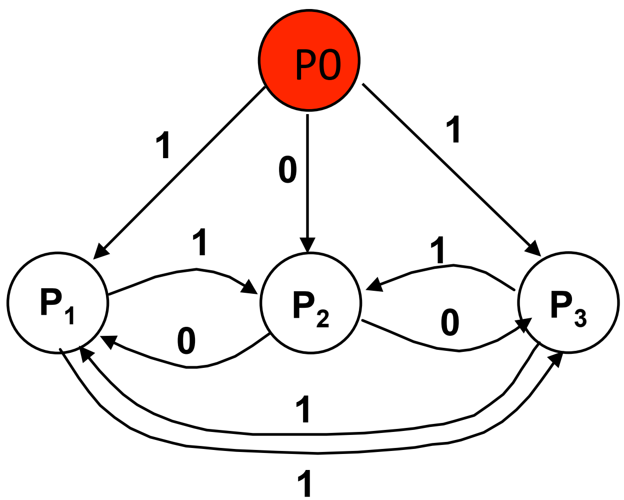
**After receiving all messages $p_1$, $p_2$, $p_3$ execute step 3 of the OM(1) to decide the majority value**

**$p_1$ received $\{1, 1, 1\} \Rightarrow 1$**
**$p_2$ received $\{1, 1, 1\} \Rightarrow 1$**
**$p_3$ received $\{1, 1, 0\} \Rightarrow 1$**

**Both conditions of the Byzantine agreement are satisfied**

# Oral Messages Algorithm OM(m) (cont.)

**Consider a system with four processes $p_0$, $p_1$, $p_2$, $p_3$**
**$p_0$ initiate the algorithm; $p_0$ is faulty**




**$P_0$ send conflicting values to $p_1$, $p_2$, $p_3$**

**Under step 1 of OM(0) $p_1$, $p_2$, $p_3$ send the received values to the other two processes**

**$p_1$, $p_2$, $p_3$ execute step 3 of OM(1) to decide on the majority value**

**$p_1$ received {1, 0, 1} $\Rightarrow$ 1**
**$p_2$ received {0, 1, 1} $\Rightarrow$ 1**
**$p_3$ received {1, 1, 0} $\Rightarrow$ 1**

**Both conditions of the Byzantine agreement are satisfied**

# Interactive Consistency by Running the Byzantine Agreement Protocol

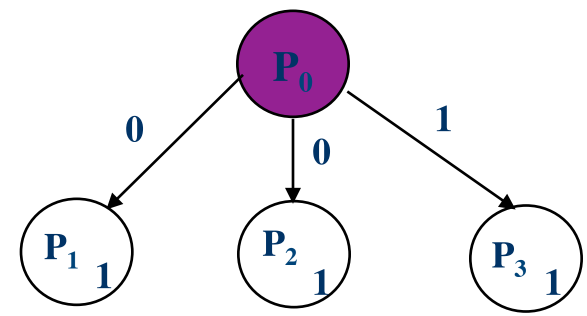
Consider a system, which consists of four processes: $p_0, p_1, p_2, p_3$
Initial values in the processes: $v_1=1, v_2=1, v_3=1, v_0=1$

Src

| | $p_0$ | $p_1$ | $p_2$ | $p_3$ |
|---|---|---|---|---|
| $P_0$ sender : $P_1$ received | 0 | | 0 | 1 |
| $P_2$ | 0 | 0 | | 1 |
| $P_3$ | 1 | 0 | 0 | |
| $P_1$ sender : $P_1$ | | | | |
| $P_2$ | 0/1 | 1 | | 1 |
| $P_3$ | 0/1 | 1 | 1 | |
| $P_2$ sender : $P_1$ | 0/1 | | 1 | 1 |
| $P_2$ | | | | |
| $P_3$ | 0/1 | 1 | 1 | |
| $P_3$ sender : $P_1$ | 0/1 | | 1 | 1 |
| $P_2$ | 0/1 | 1 | | 1 |
| $P_3$ | | | | |

majority

own value

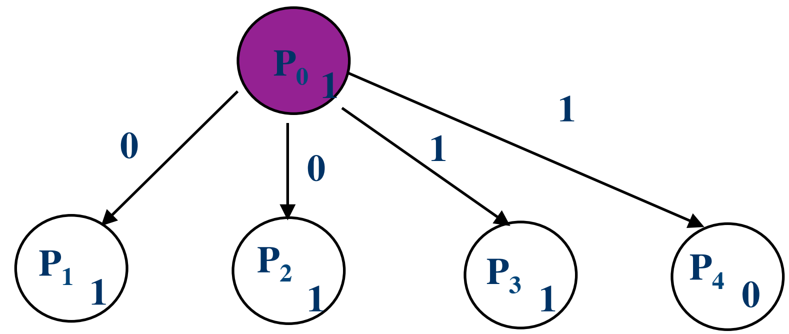



$P_1=\{0,1,1,1\}$ ==> 1
$P_2=\{0,1,1,1\}$ ==> 1
$P_3=\{0,1,1,1\}$ ==> 1

**Vectors in each process** **Final decision**

# Interactive Consistency by Running the Byzantine Agreement Protocol

| Sender | Received | $p_0$ | $p_1$ | $p_2$ | $p_3$ | $p_4$ |
|---|---|---|---|---|---|---|
| $P_0$ sender : | $P_1$ received | 0 | | 0 | 1 | 1 |
| | $P_2$ | 0 | 0 | | 1 | 1 |
| | $P_3$ | 1 | 0 | 0 | | 1 |
| | $P_4$ | 1 | 0 | 0 | 1 | |
| $P_1$ sender : | $P_1$ | | | | | |
| | $P_2$ | 0/1 | 1 | | 1 | 1 |
| | $P_3$ | 0/1 | 1 | 1 | | 1 |
| | $P_4$ | 0/1 | 1 | 1 | 1 | |
| $P_2$ sender : | $P_1$ | 0/1 | | 1 | 1 | 1 |
| | $P_2$ | | | | | |
| | $P_3$ | 0/1 | 1 | 1 | | 1 |
| | $P_4$ | 0/1 | 1 | 1 | 1 | |
| $P_3$ sender : | $P_1$ | 0/1 | | 1 | 1 | 1 |
| | $P_2$ | 0/1 | 1 | | 1 | 1 |
| | $P_3$ | | | | | |
| | $P_4$ | 0/1 | 1 | 1 | 1 | |
| $P_4$ sender : | $P_1$ | 0/1 | | 0 | 0 | 0 |
| | $P_2$ | 0/1 | 0 | | 0 | 0 |
| | $P_3$ | 0/1 | 0 | 0 | | 0 |
| | $P_4$ | | | | | |




$P_1$={0,1,1,1,0}==> 1

$P_2$={0,1,1,1,0}==> 1

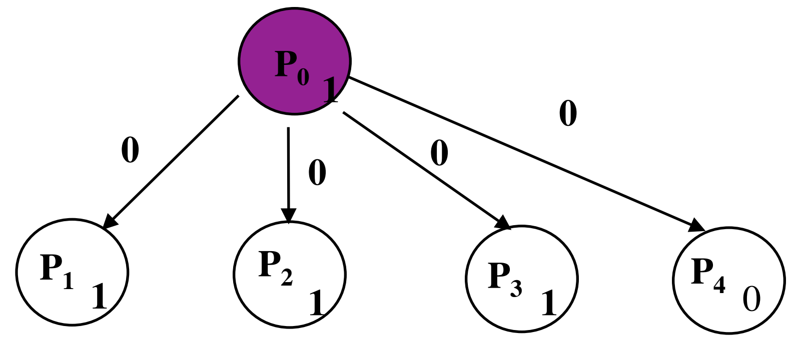
$P_3$={0,1,1,1,0}==> 1

$P_4$={0,1,1,1,0}==> 1

**Vectors in each process** **Final decision**

# Interactive Consistency by Running the Byzantine Agreement Protocol

| | $p_0$ | $p_1$ | $p_2$ | $p_3$ | $p_4$ |
|---|---|---|---|---|---|
| $P_0$ sender : $P_1$ received | 0 | | 0 | 0 | 0 |
| $P_2$ | 0 | 0 | | 0 | 0 |
| $P_3$ | 0 | 0 | 0 | | 0 |
| $P_4$ | 0 | 0 | 0 | 0 | |
| $P_1$ sender : $P_1$ | | | | | |
| $P_2$ | 0/1 | 1 | | 1 | 1 |
| $P_3$ | 0/1 | 1 | 1 | | 1 |
| $P_4$ | 0/1 | 1 | 1 | 1 | |
| $P_2$ sender : $P_1$ | 0/1 | | 1 | 1 | 1 |
| $P_2$ | | | | | |
| $P_3$ | 0/1 | 1 | 1 | | 1 |
| $P_4$ | 0/1 | 1 | 1 | 1 | |
| $P_3$ sender : $P_1$ | 0/1 | | 1 | 1 | 1 |
| $P_2$ | 0/1 | 1 | | 1 | 1 |
| $P_3$ | | | | | |
| $P_4$ | 0/1 | 1 | 1 | 1 | |
| $P_4$ sender : $P_1$ | 0/1 | | 0 | 0 | 0 |
| $P_2$ | 0/1 | 0 | | 0 | 0 |
| $P_3$ | 0/1 | 0 | 0 | | 0 |
| $P_4$ | | | | | |




$P_1$={0,1,1,1,0}==> 1

$P_2$={0,1,1,1,0}==> 1

$P_3$={0,1,1,1,0}==> 1

$P_4$={0,1,1,1,0}==> 1

**Vectors in each process** **Final decision**

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- Issues in design of distributed systems
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# Paxos: Problem

- Most failures are not Byzantine in the real world → BFT protocols are an over-kill
- Consensus under non-byzantine faults
  - Can be achieved with 2f + 1 processes
  - Assumes crash-stop-recovery failure semantics
  - Assumes network can lose or reorder messages
  - Requires at most 4f + 4 messages in fault-free case

# Paxos: Principals

- **Proposer: Node that initiates the protocol**
  - Proposes an initial value to agree upon
  - May be more than one proposer to start with
  - **Leader:** A distinguished, trusted proposer

- **Acceptor: All other nodes that participate**
  - Can reject the proposal from the proposer
  - Can agree with the proposal, but is prevented from agreeing to proposals from other proposers

# Paxos: Properties

- **Non-triviality**
  - The value learned is one of the proposed ones
- **Safety:**
  - At most of the proposed values is learned
- **Liveness:**
  - Eventually, all non-faulty acceptors will learn it

# Paxos: Proposal Numbers

- Because multiple proposers can be active, we need a way to distinguish proposals
  - Assume that there is a global mechanism to sequence proposals from 1 .. N

- An acceptor accepts a proposal with value m if and only if it has not responded to a proposal with value higher than m (with a promise)

# Paxos Algorithm: Phase 1

- **Proposer** selects a proposal number n and sends a prepare request with number n to a majority of acceptors (quorum)
- If an **acceptor** receives a prepare request with number ‘n’ greater than that of any prepare request to which it has already responded, then it responds with a promise not to accept any more proposals numbered less than n and with the highest-numbered proposal that it has accepted.

# Paxos Algorithm: Phase 2

- If the proposer receives a response to its prepare requests numbered n from a majority of acceptors, then it sends an accept request to each of those acceptors numbered n with a value v, where v is the value of the highest-numbered proposal among the responses, or is any value.
- If an acceptor receives an accept request for a proposal numbered n, it accepts the proposal unless it has already responded to a prepare request having a number greater than n.

# Termination

- How do we tell if a value has been learned by a majority of the processes ?
  - Solution: Have specially designated processes called Learners, which keep track of the accepted values. Acceptors send their responses to Learners, who may then communicate with other learners to spread the information
  - Message loss may prevent learners from ever finding out the value accepted by a quorum

# Paxos: Failure modes

- More than one proposer
- Failures of proposer, acceptor (non-majority) or learners
- Network failures among any pairs of links
- Failure of leader (rare event)

# Paxos: Message Complexity

- Failure-free operation:
  - Phase 1: Proposer sends f + 1 messages
  - Acceptors provide f + 1 responses
  - Phase 2: Proposer sends f + 1 messages and receives another f + 1 responses

- Total number of messages = 4f + 4

Compared to OM(n) protocol, this is much lower

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